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Design of a Pool Access Device

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Design of a Pool Access Device

A Major Qualifying Project (MQP) Report

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

in Mechanical Engineering

By

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April 29, 2013

Approved

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Abstract

January 31, 2013 marked the extended deadline of compliance set forth by the federal government under the revised ADA (American Disabilities Act) specifically for public accessible pools. When a pool is “accessible,” under those standards, it has an entry and exit that accommodates everyone specifically those with disabilities. This act is not limited to public pools but also includes some private businesses such as hotels, spas and wading pools. The pool lifts on the market today can be expensive and also be expensive to install. The goal is to safely move a person in a waterproof chair from the deck of the pool, to over the water, into the pool, and when the user is finished, safely remove them from the pool back to deck. Part of this goal is keeping the chair as horizontal as possible. The design has been developed using the 2010 ADA standards for accessible design. The ADA standards indicate how far the center of the seat of chair should be from the pool, how high the seat of chair should be from pool deck, and how deep the seat of the chair should be submerged below water. The design uses a parallel four-bar linkage mechanism and is able to lift the chair with an average weight person in and out of the pool.

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Introduction

Under the ADA (Americans with Disabilities Act) the federal government has mandated that all pools have handicap access. ADA compliance is required for Title II and Title III pool facilities by January 31, 2013. Both public and private facilities are affected by this new ADA standard for pool lifts. to design a low cost removable handicap access chair for their pools. The problem is to design the mechanism to move a waterproof chair and a person seated in it from above the pool deck into the water.

Background research

Benchmarking

Aqua Creek Products is a company that builds commercial and residential pool lifts. The company offers different models of the pool lifts, and the main mechanisms they have been using are four-bar and arm swing.

This is a manual operation arm swing pool lift from this company. The lift uses a linear actuator with a lever to operate the lift. The submerge position is shown in Figure 1. Figure 2 shows the loading position of the lift. This lift requires an assistant to operate the lift for the user as shown in Figure 3. This model is one of their old products, it does not comply with the new ADA standards because the user cannot self-operate the lift.

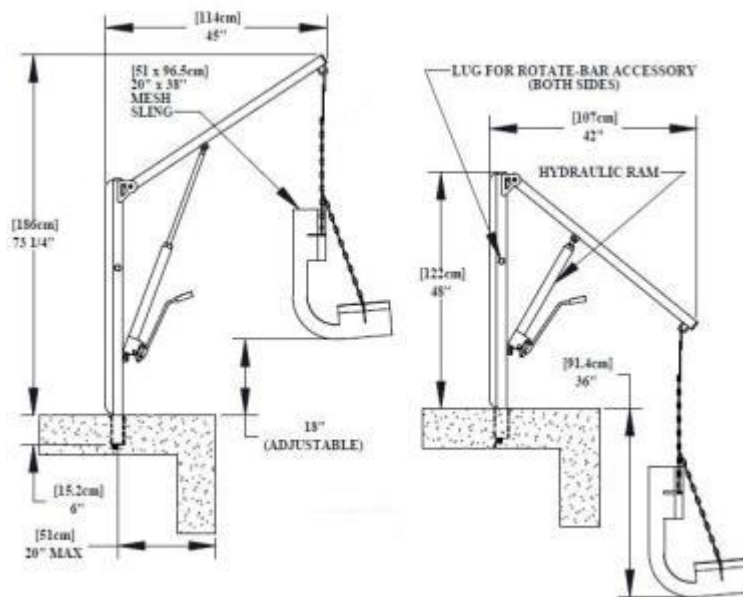


Figure 1: Design specifications of the lift at initial lowering position with the linear actuator fully extended (left) and extreme submerged position (right) with the linear actuator fully retracted.



Figure 2: Loading position of the lift with the linear actuator fully extended.



Figure 3: The assistant is operating the lift to lower the user into the water.

Spectrum Aquatics manufactures products that are used in construction, operation and maintenance of commercial swimming pools and spas. The company has portable pool lifts that uses four-bar mechanism, and most of their models are powered by linear actuator.

The lift shown in Figure 4 is one of the ADA compliant pool lift; the right picture is the isometric view of the product. This product could be both in-ground and on ground pool lift depends on the needs of the facility. The one shown in Figure 4 is the in-ground version. This lift uses four-bar mechanism and it is self-operational. It also has a non-slip grip and a foot rest to increase the safety and user friendliness of the product, the non-slip grip is the overhead transfer assist shown in Figure 5.

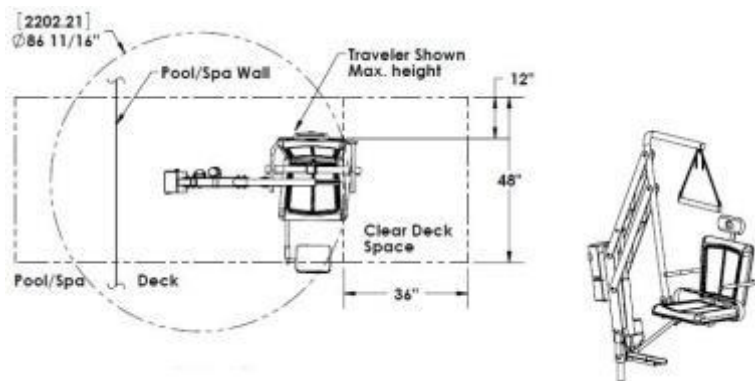


Figure 4: The top view and the isometric view of the lift.

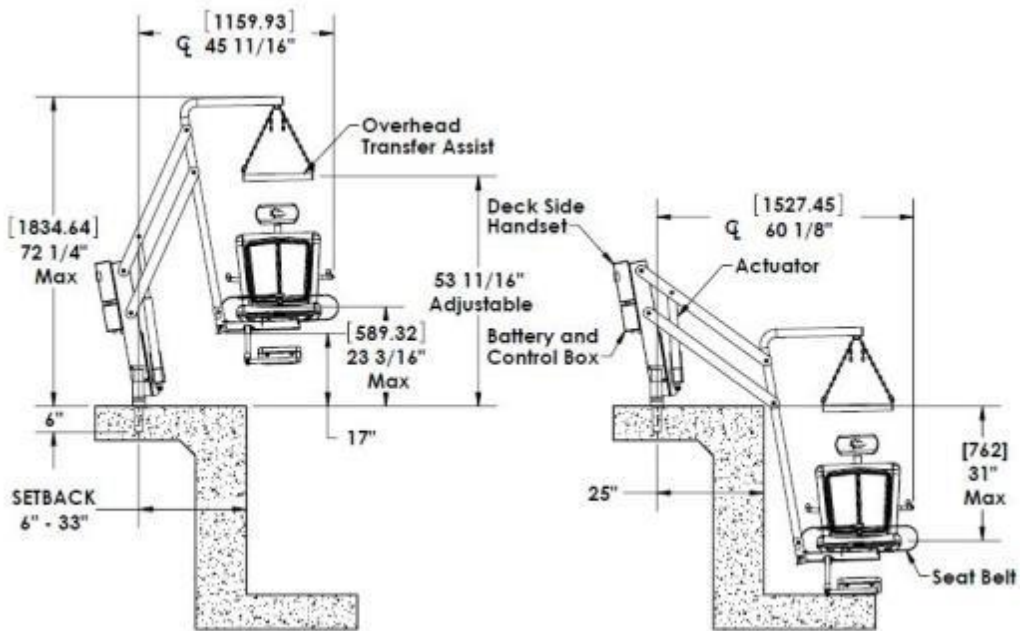


Figure 5: The side view of the lift. On the left is the chair is in the highest position with the linear actuator fully extended and the lowest position is on the right with the linear actuator fully retracted.

Goal Statement

Design a pool lift that safely raises and lowers a person from the deck of a pool into the water without tipping the user out of the chair.

Task Specifications

The list below is the complete task specifications of our designs. The purpose of the list is to meet the ADA standards and also help the group to design a user friendly product.

1. The lift must be ADA compliant (ADA compliance is required for Title II and Title III pool facilities by January 31, 2013.):
 - Minimum Lifting Capacity of 300 lbs.
 - Lift must have a foot rest.
 - The Assembled lift must be installed where the pool depth does not exceed 48in. unless the entire pool depth is greater than 48in.
 - The centerline of the seat must be no less than 16in. from the edge of the pool
 - The mechanism shall be operated in the clear deck space and shall have a slope no steeper than 1:48.
 - The left edge of the seat must be clear for 36in. to its' left while clear 36in. from the backrest to out front of the chair and clear 12in. from the backrest of the seat extending behind.
 - The seat base must be 16in. in width min.
 - The top of the seat must clear a height of 16-19in. from the ground.
 - The top of the seat must be submerged at least 18in. when lowering the passenger.
 - User must be able to operate, without assistance, from the deck and water
 - Must not require tight grasping, pinching or twisting of the wrists to operate and not require more than 5 lbs. of force.
2. A linkage solution is desired
3. The components of the lift must be corrosive resistant.
4. The components of the lift must be secured the ground before use.
5. The lift must move passengers from the ground into the pool safely and smoothly. The chair must not fall or tip and the operation must stay stable and must not expose the user to unsafe accelerations.
6. Mechanism must not exceed \$600.
7. The components of the lift must fit through a door 77in. x 36in.
8. The lift must be sturdy and stable in a wet environment.
9. The lift must be user friendly.
10. The water depth at the access point could be anywhere from 4 feet.
11. Assistant must be able to install the lift in place in 15 minutes or less.
12. Assistant must be able to remove the lift in 15 minutes or less.
13. The lift cannot be permanently attached to the pool deck or sides.
14. The lift cannot damage any tile of the pool or pool area during operation or installation.
15. The lift must move one user at a time.
16. Must sustain long periods of use.
17. The lift should be ideally easy to maintain.
18. The lift should be able to adapt in an outdoor or indoor environment.
19. The lift should be able to adapt to various pool configurations.

Preliminary design

Four Bar Design

The “Four Bar design” design consists mainly of a four metal links, a linear actuator motor to move the links attached to the chair up and down the z-axis as shown in (Fig.6). The other important parts of this design are the bases 1 and 2, the motor in base one that rotates the chair 90 °about the z-axis, and the chair that attaches to the four metal links (B) with a series of bolts and screws. The design will be placed pool side where the water does not exceed 4 ft as shown in (Fig.6) unless the entire pool has a depth greater than 4 ft. The design also must be set up in a location where there is 12 in. free from behind and 36 in. free from the edge of the chair opposite the pool as shown in (Fig.7).The next section describes the parts and function of each part.

Base 1 in (Fig.6) will house a motor that turns Base 2 90 °about the z-axis as seen in the top view of the design in (Fig.7) with the help of a gear system (A) shown in (Fig.8). Base 1 has wheels attached to bottom for portability. The wheels will lock into place to ensure it is fixed in the desired location. Each base is 3ft. by 3ft as shown in the top view (Fig.7). The top base (base 2) will accommodate the linear actuator (C) shown in (Fig.8) as seen in the core components view. Base 2 has the attachment points for the linkage system (Fig.8). The Rotating gear system (A) consists of an inner gear and an outer gear to control the speed of the motor rotating base 2.A motor will be bolted in base 1 to drive the inner gear of the rotating gear system. (Fig.7) shows the top view of the system. The four bar mechanism (B) also showed in (Fig.8) illustrates the linear actuator motor and its connection to the lower metal link (Link 2). The links attach to the chair in four locations to improve stability. The motor will be bolted to the inside of base 2. The four bar mechanism attaches one link to base 2 on one side, the third link is the chair attaching to the metal links through a pin joint, the fourth link attaches to the upper part of the chair and back to base 2 on the upper attachment point. The configuration is repeated on the other side of base 2 as shown in (Fig.6) and (Fig.8). The four bar mechanism essentially translates the patient up and down the z-axis but moves the chair through rotations about the y-axis as shown in (Fig.6). The chair will move 18 in. below the water line allowing for the user to enter the water and complying with the ADA standards.

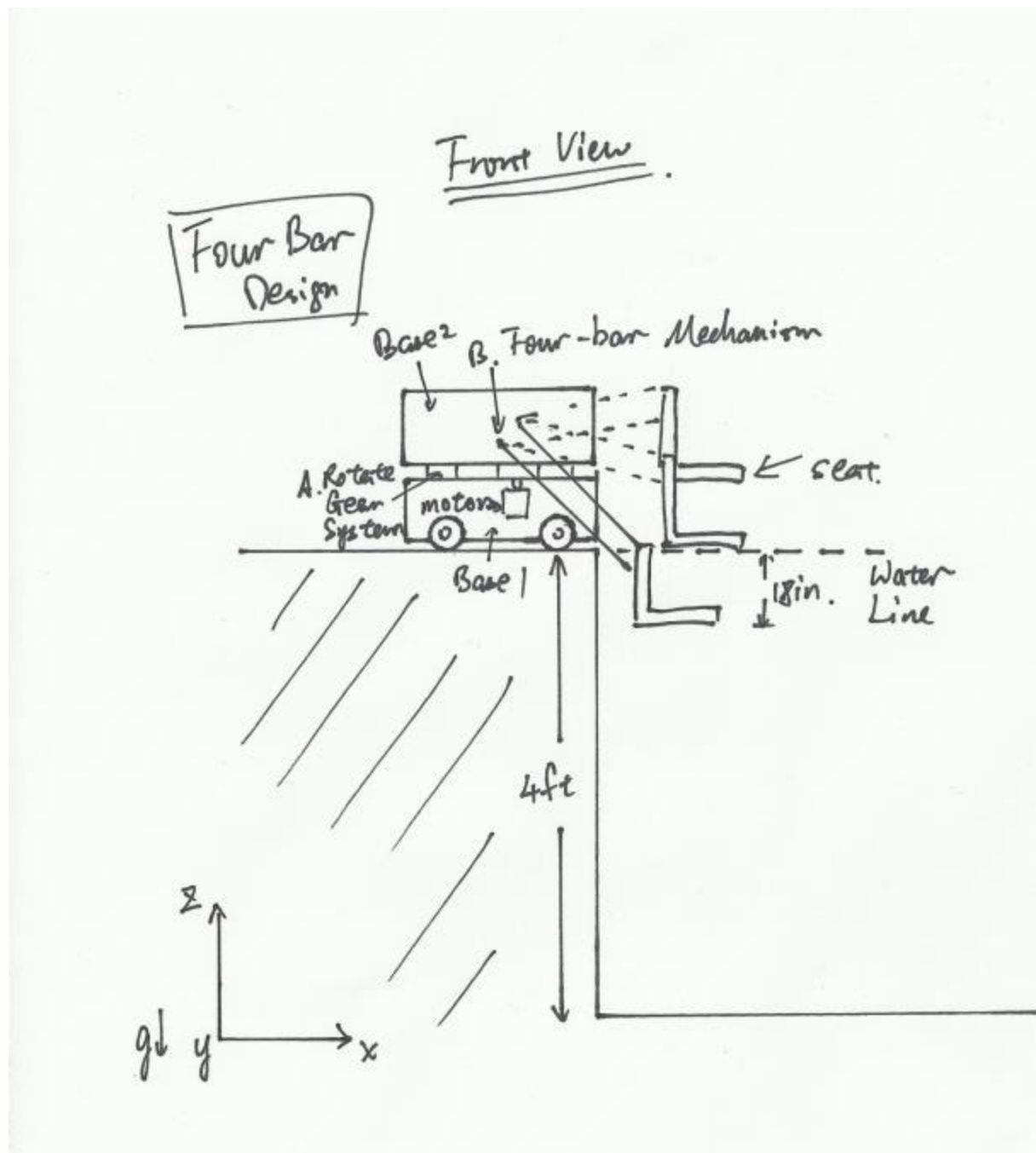


Figure 6: Front view of the design with extreme high position and extreme submerge position.

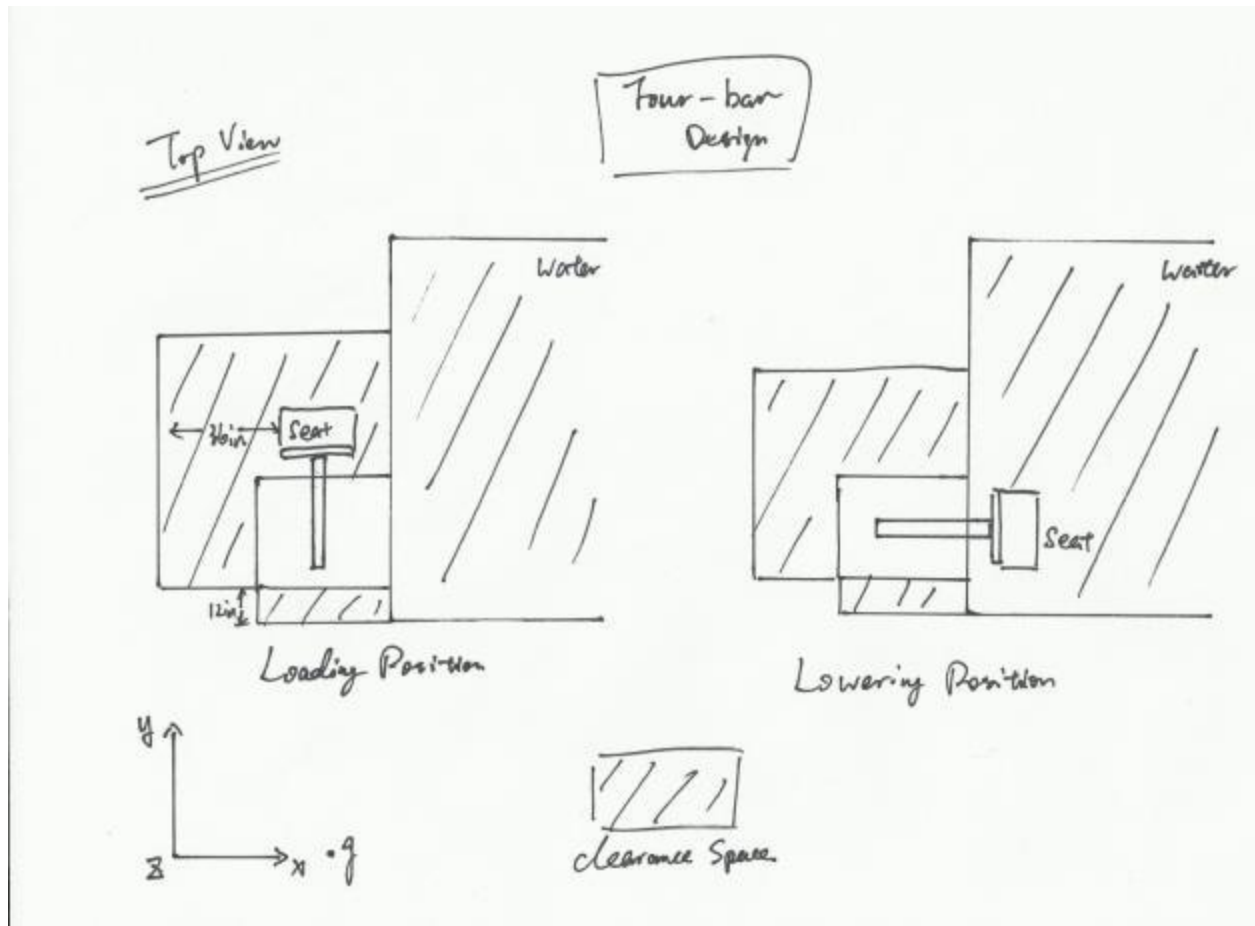
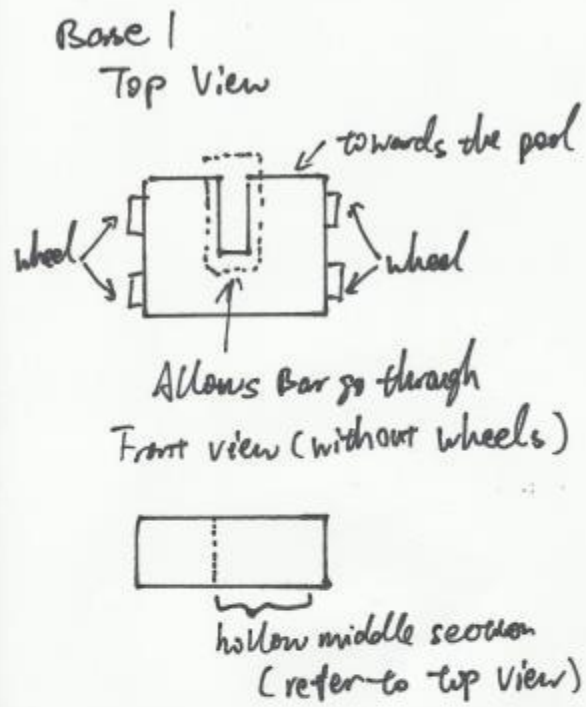
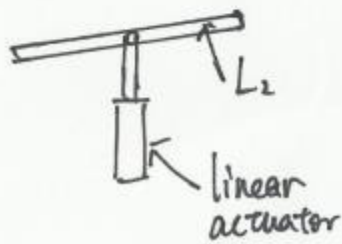


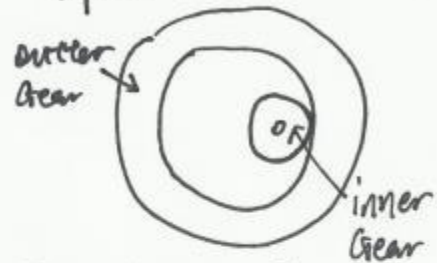
Figure 7: Top view of the design with loading position and lowering position.



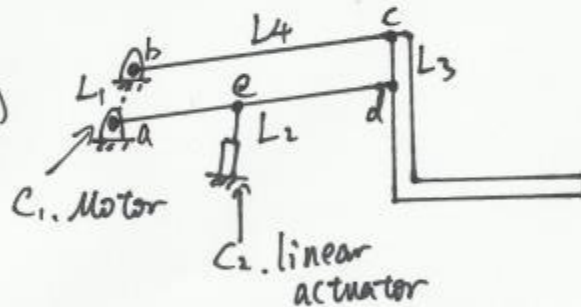
C₂. Linear Actuator



A. Rotace Gear System
top view



B. Four-bar Mechanism.
Linkage system
(Loading Position only)



$$L_1 = \frac{1}{2} \text{ ft}$$

$$L_2 = 3 \text{ ft}$$

$$L_3 = \frac{3}{4} \text{ ft}$$

$$L_4 = 3 \text{ ft}$$

Figure 8: The core components of the four bar linkage design.

Table 1 show the operation steps and the power options that could be used for the four bar design.

Table 1: Operation steps and the power options that could be used for four bar design.

Four Bar		
Steps	Operation	Power Sources
Step 1	Turning user 90 °to load position	1. A motor can be attached to a gear system to turn the base part, shown in Figure 7.
Step 2	Rotate the bars to put user into water	1. A motor can be attached to a gear system that is on the pin joints of the mechanism to drive the bars, shown in Figure 6. 2. A linear Actuator can be attached to L2 to drive the bars, shown in Figure 6.
Step 3	Lift the User out of the water	1. A motor can be attached to a gear system that is on the pin joints of the mechanism to drive the bars, shown in Figure 6. 2. A linear Actuator can be attached to L2 to drive the bars, shown in Figure 6.
Step 4	Rotate 90 °back to standby position	1. A motor can be attached to a gear system to turn the base part, shown in Figure 7.

Straight-line Linkage Design

The “Straight line Linkage” design consists mainly of a four metal bar links, a slot to limit the movement of the of the link that is connected to the chair to one translation up and down the z-axis, a linear actuator motor to power it that is attached to link 3 all of which is shown in (Fig.9). The other important parts of this design are the bases 1 and 2, the motor in base one that rotates the chair 90 °about the z-axis, and the chair that attaches to the sliding mechanism (C) with a series of bolts and screws. The design will be placed pool side where the water does not exceed 4 ft. as shown in (Fig.9) unless the entire pool has a depth greater than 4 ft. The design also must be set up in a location where there is 12 in. free from behind and 36 in. free from the edge of the chair opposite the pool as shown in (Fig.10).The next section describes the parts and function of each part.

Base 1 in (Fig.9) will house a motor that turns Base 2 90 °about the z-axis as seen in the top view of the design in (Fig.10) with the help of a gear system (A) shown in (Fig.11). Base 1 has wheels attached to bottom for portability. The wheels will lock into place to ensure it is fixed in the desired location. Each base is 3ft. by 3ft as shown in the top view (Fig.10). The top base (base 2) will hold the linear actuator (C) shown in (Fig.11) as seen in the front view. Base 2 also holds the entire linkage system (Fig.9). The rotating gear system (A) consists of an inner gear and an outer gear to control the speed of the motor rotating base 2.A motor will be bolted in base 1 to drive the inner gear of the rotating gear system. (Fig.9) shows the top view of the system. The linear actuator motor (B) also showed in (Fig.11) illustrates the motor attaching to link three which will move the third link to create the straight line motion with link 5. The motor will be bolted to the inside of base 2. The rack (C) will complement the T-insert inside it when as shown in (Fig.10) and (Fig.11) will be attached to base 2. This slider insert is meant to keep link 5 vertical to ensure it has one translation to ensure it is a straight line linkage. The slider (C) mechanism as shown as a top view in (Fig.10) shows the configuration of the slider to keep the chair from disconnecting and unnecessary movement. The C shaped rack wraps around the T shaped insert. The T-shaped insert (D) shown in (Fig.11) will be bolted to the chair. The slider is meant to allow the n as seen in (Fig. 9) translation of the chair in the z-axis as shown in (Fig.9). The chair will move 18 in. in the negative z direction below the water line allowing for the user to enter the water and complying with the ADA standards.

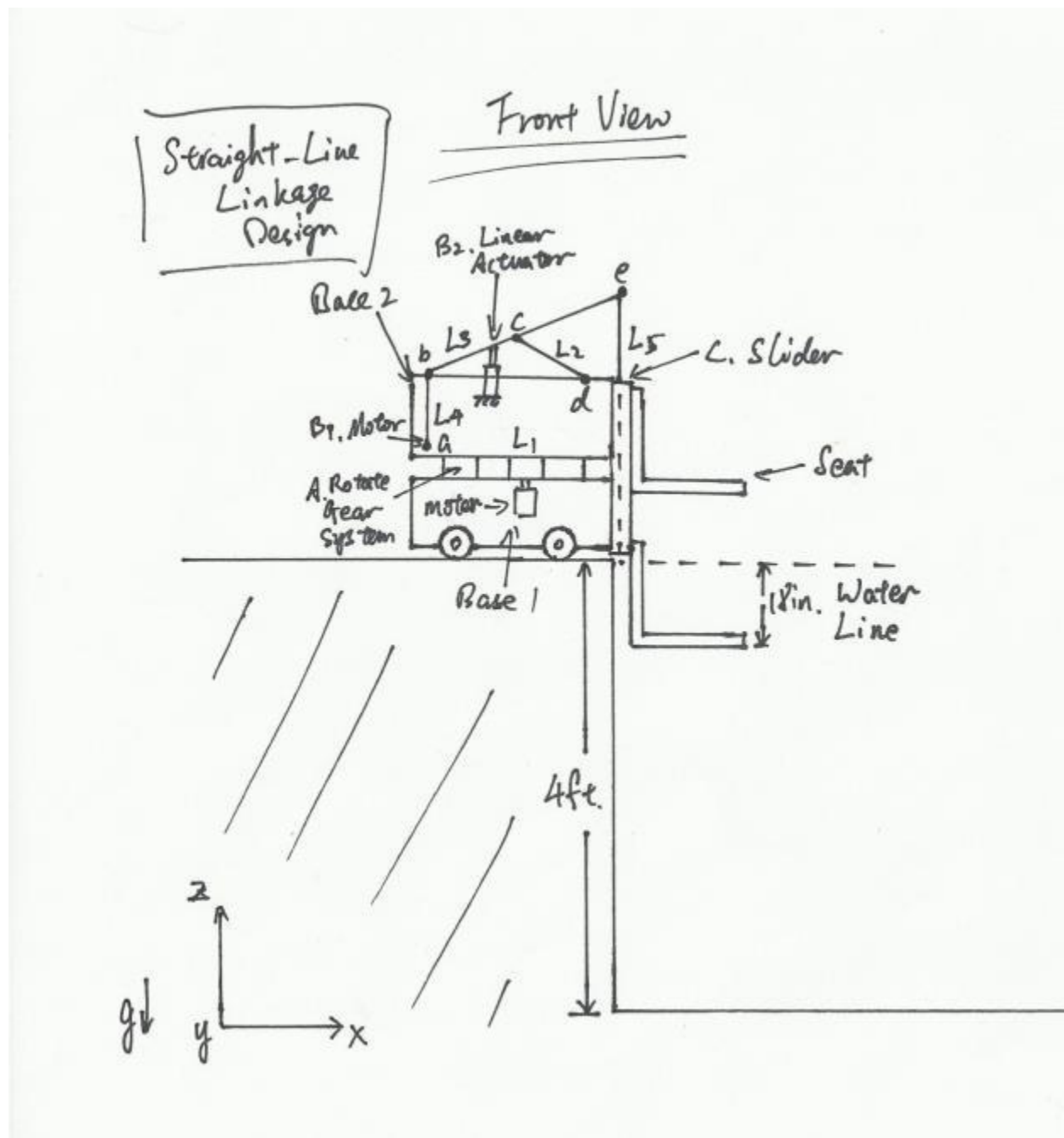


Figure 9: Front view of the design with extreme high position and extreme submerge position.

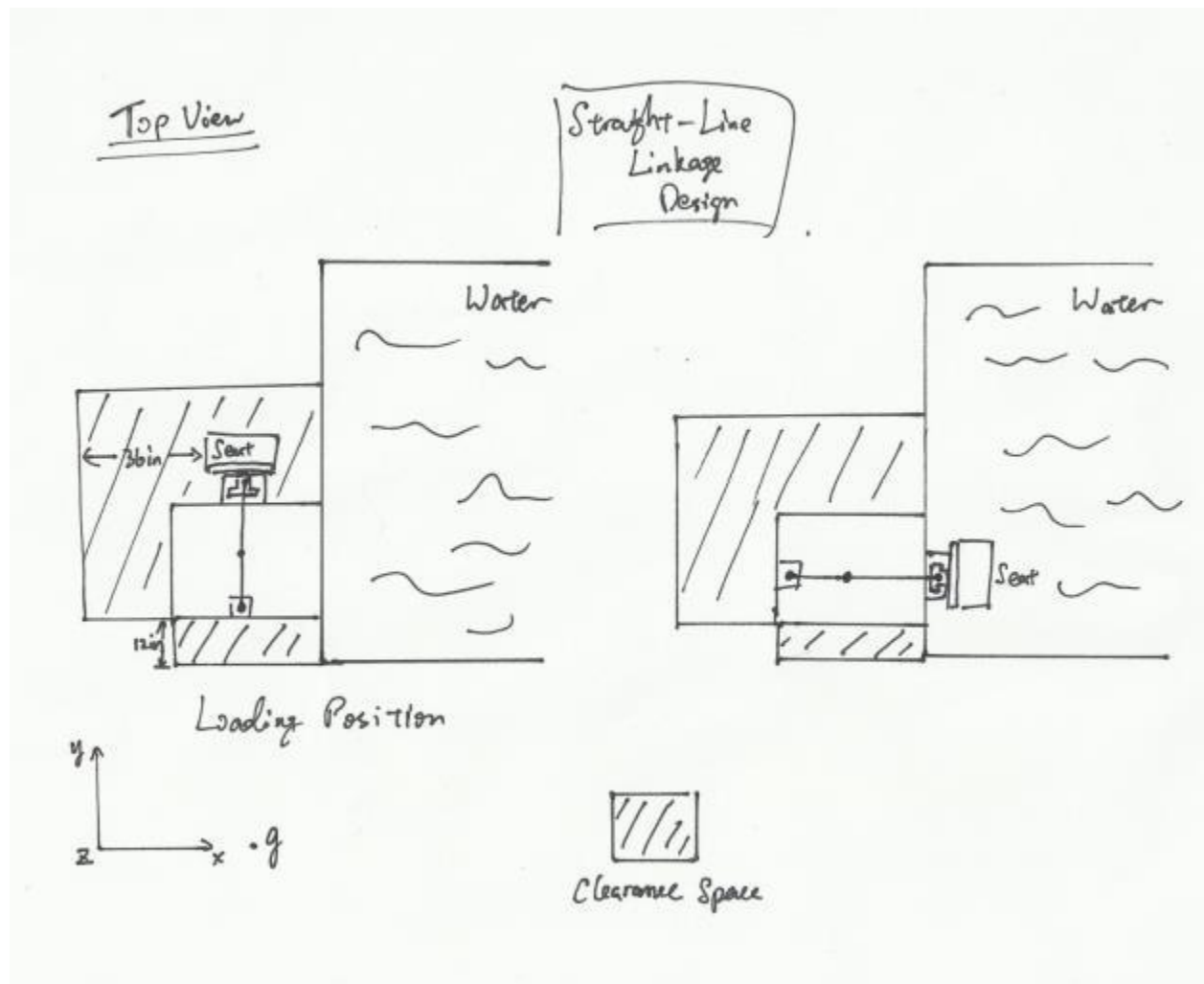


Figure 10: Top view of the design with loading position and lowering position.

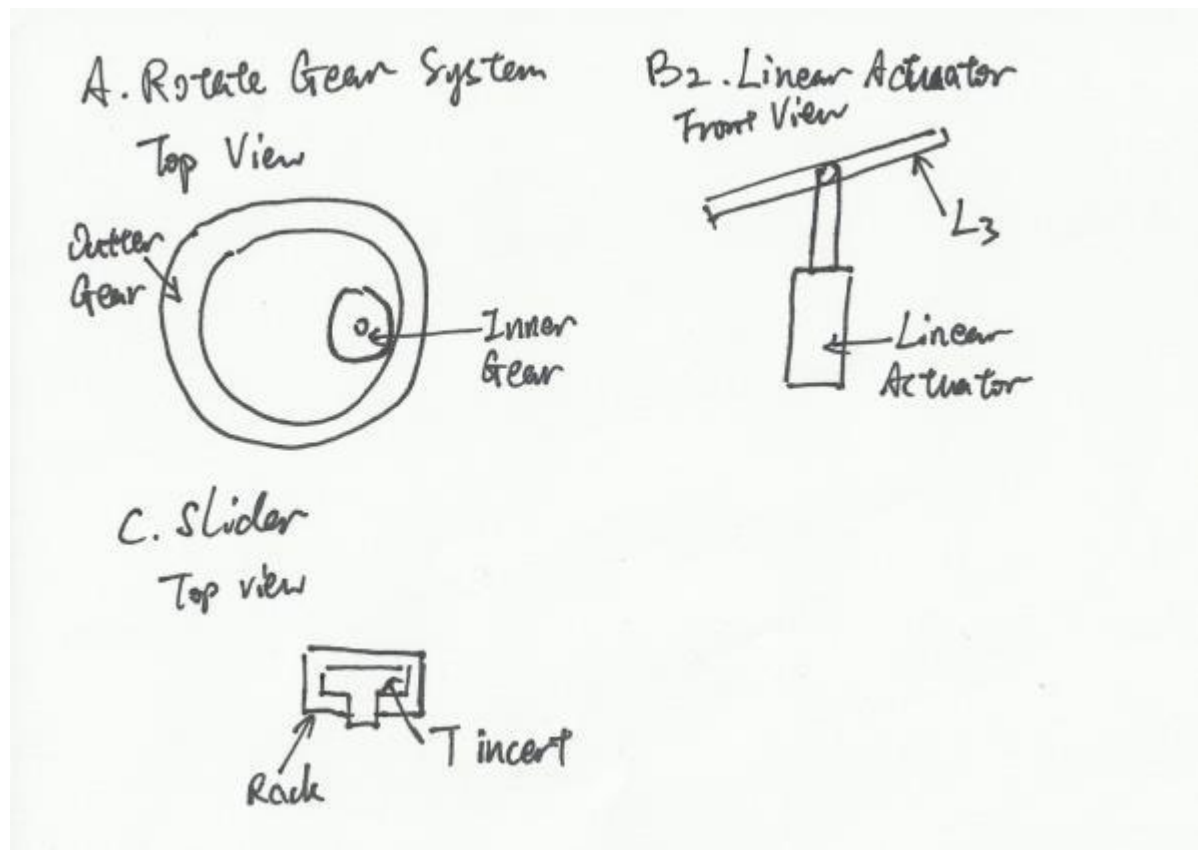


Figure 11: The core components of the straight-line linkage design.

Table 2 is the operation steps and the power options that could be used for Straight-line linkage design.

Table 2: operation steps and the power options that could be used for Straight-line linkage

Straight-line linkage		
Steps	Operation	Power Sources
Step 1	Turning user 90 °to load position	1. A motor can be attached to a gear system to turn the base part, shown in Figure 10.
Step 2	Lower link 3 into the water with the user in the chair	1. A motor can be attached to a gear system that is on the pin joints of the mechanism to drive the bars, shown in Figure 9. 2. A linear Actuator can be attached to L3 to drive the bars, shown in Figure 9.
Step 3	Raise the user out of the water	1. A motor can be attached to a gear system that is on the pin joints of the mechanism to drive the bars, shown in Figure 9. 2. A linear Actuator can be attached to L3 to drive the bars, shown in Figure 9.
Step 4	Turn the user back to the standby position	1. A motor can be attached to a gear system to turn the base part, shown in Figure 10.

Pulley/Cable with Slider Design

The “Pulley Cable with a Slider” design consists mainly of a cable, a wheel to limit the movement of the cable, a motor to power it that is attached to a gear system and a drum, and a slider mechanism to limit the freedom of the chair to one linear translation up and down the z axis as shown in (Fig.12). The other important parts of this design are the bases 1 and 2, the motor in base one that rotates the chair 90 ° about the z-axis, and the chair that attaches to the sliding mechanism (D) with a series of bolts and screws. The design will be placed pool side where the water does not exceed 4 ft. as shown in (Fig.12) unless the entire pool has a depth greater than 4 ft. The design also must be set up in a location where there is 12 in. free from behind and 36 in. free from the edge of the chair opposite the pool as shown in (Fig.13). The next section describes the parts and function of each part.

Base 1 in (Fig.12) will house a motor that turns Base 2 90 ° about the z-axis as seen in the top view of the design in (Fig.13) with the help of a gear system (A) shown in (Fig.14). Base 1 has wheels attached to bottom for portability the wheels will lock into place to ensure it is fixed in the desired location. Each base is 3ft. by 3ft as shown in the top view (Fig.13). The top base (base 2) will house the pulley motor (B) shown in (Fig.14) as seen in the front view. Base 2 also holds the pulley’s cable, the pulley wheel (C), and the sliding mechanism (D) shown in (Fig.14). The Rotating gear system (A) consists of an inner gear and an outer gear to control the speed of the motor rotating base 2. A motor will be bolted in base 1 to drive the inner gear of the rotating gear system. (Fig.13) shows the top view of the system. The pulley motor (B) also showed in (Fig.13) illustrates the motor and drum that will have the cable attached to it. The cable will roll in between the walls attached to the motor box. The motor will be bolted to the inside of base 2. The Pulley wheel (C) as shown in (Fig.12) and (Fig.13) will be attached to base 2 by two bars and a pin joint to allow rotation of the wheel but keep it in place. The slider (D) mechanism as shown as a top view in (Fig.14) shows the configuration of the slider to keep the chair from disconnecting and unnecessary movement. The C shaped rack wraps around the T shaped insert. The T-shaped insert (D) shown in (Fig.14) will be bolted to the chair. The slider is meant to allow the translation of the chair in the z-axis as shown in (Fig.12). The chair will move 18 in. below the water line allowing for the user to enter the water and complying with the ADA standards.

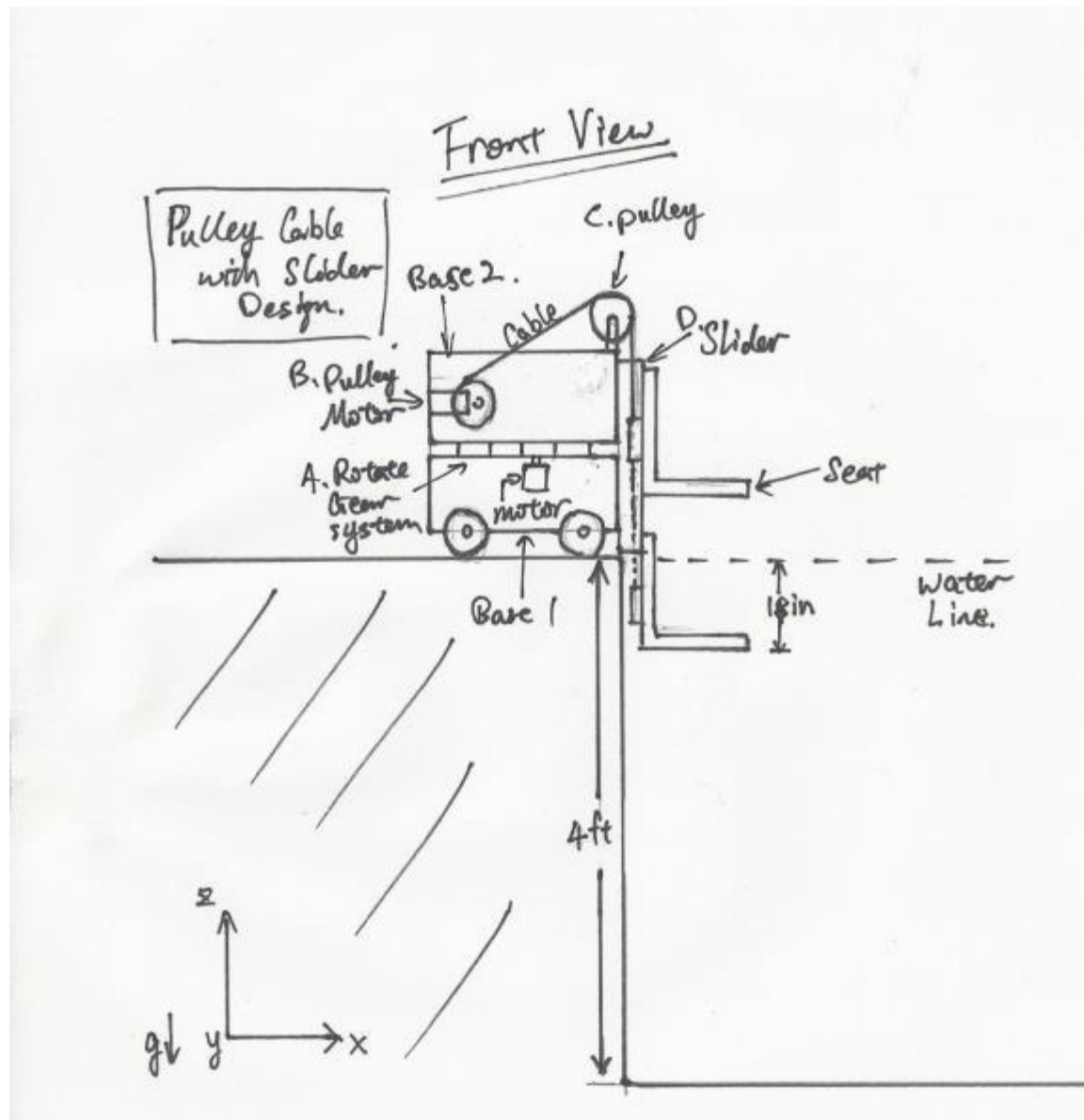


Figure 12: Front view of the pulley cable with slider design.

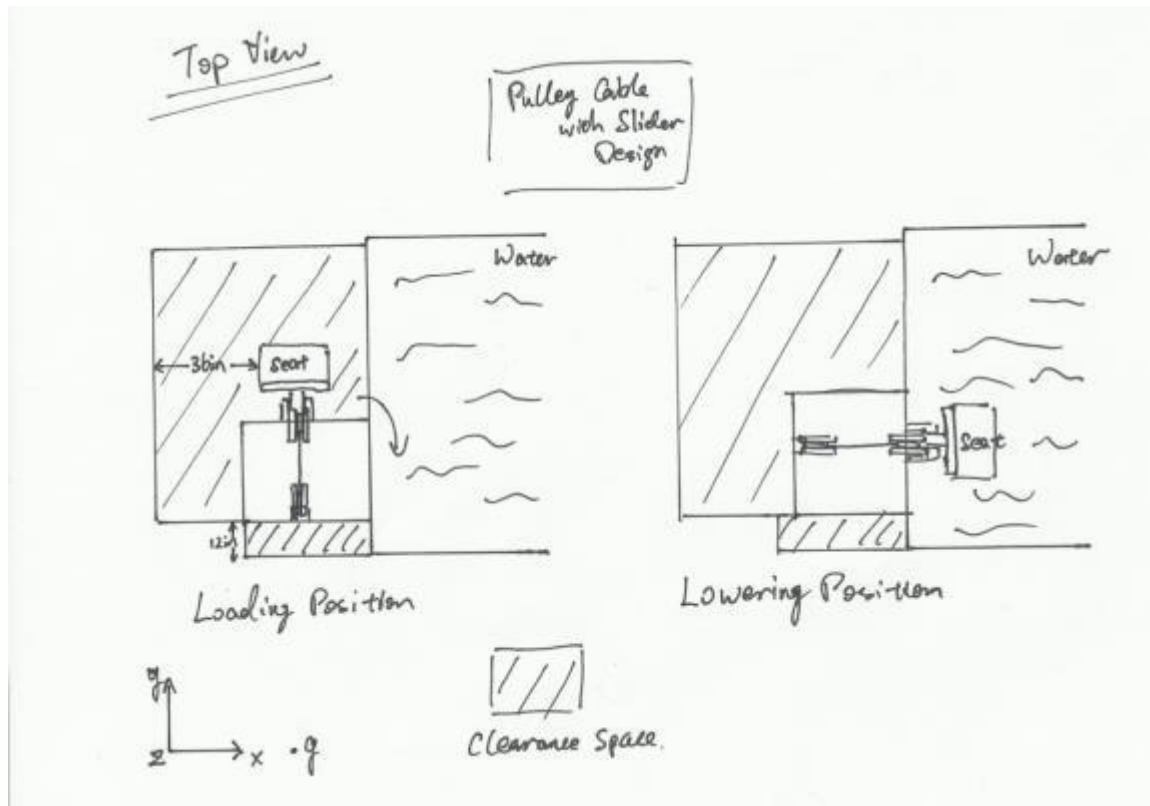


Figure 13: Top view of loading and lowering position of the pulley cable with slider design.

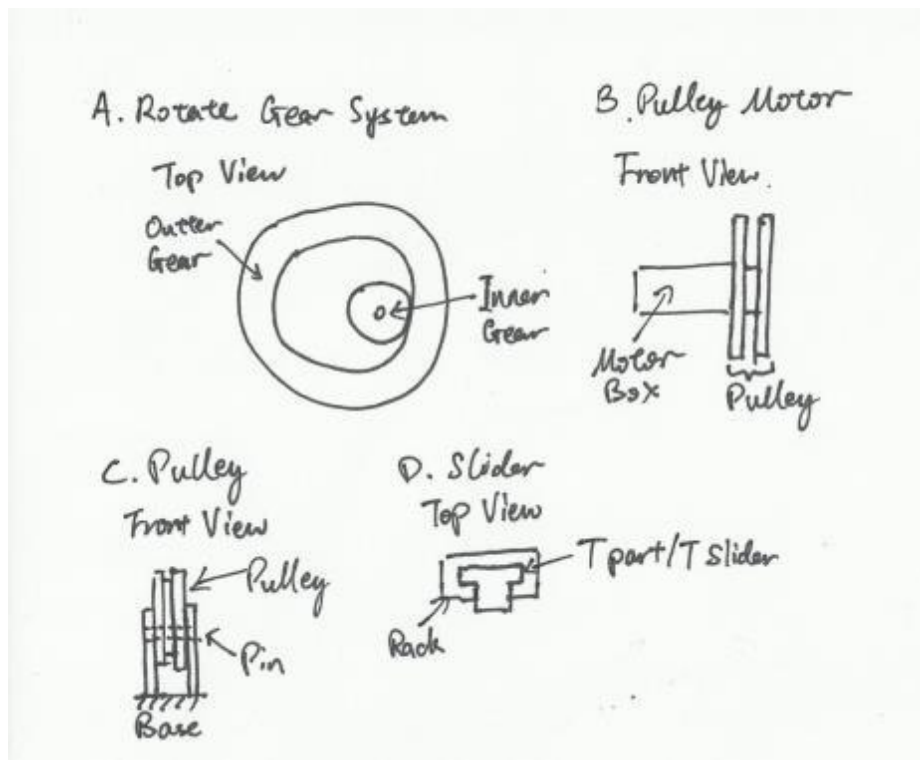


Figure 14: Core components of the pulley cable with slider design

Scissor Lift

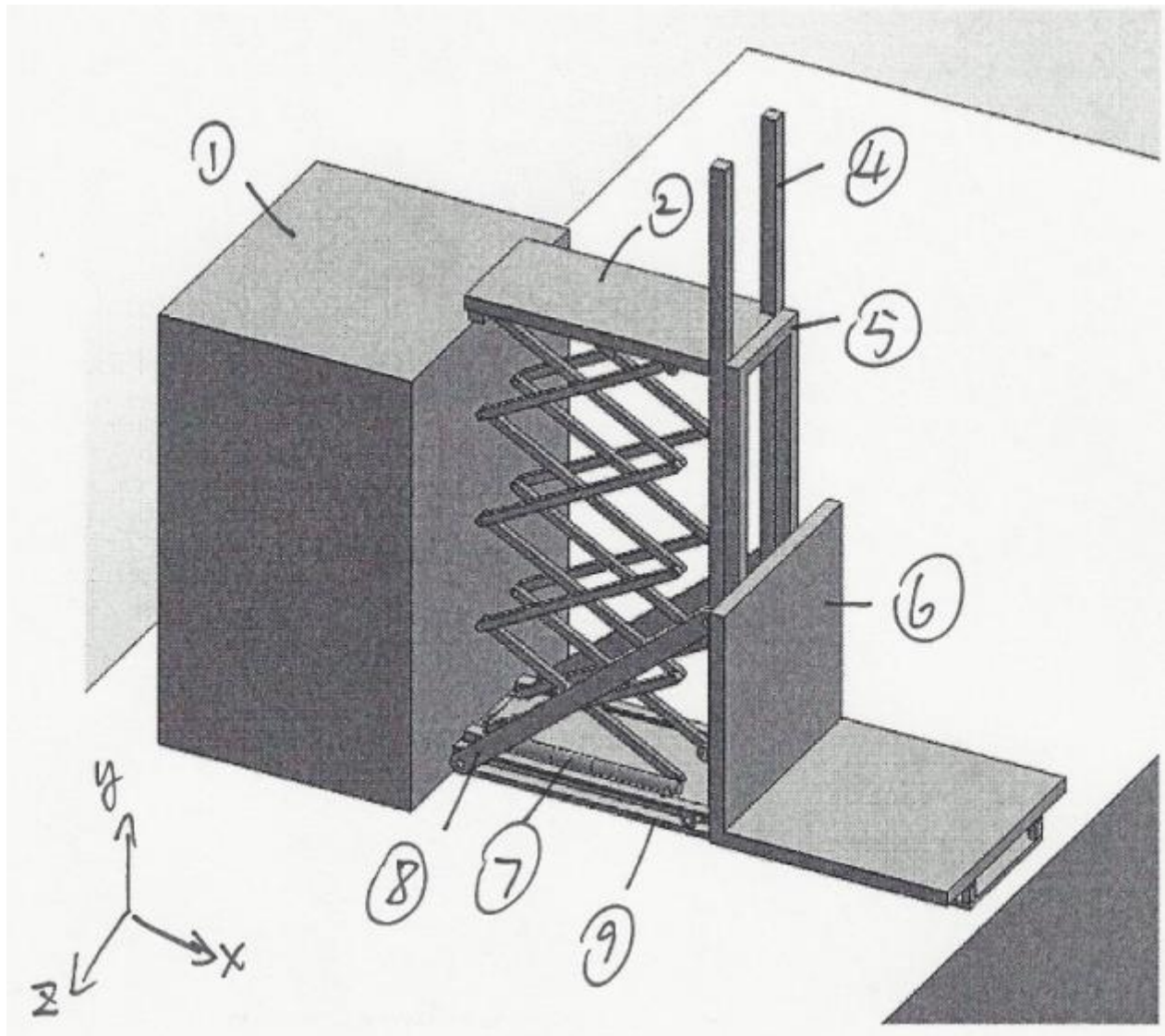


Figure 15: Isometric View of the scissor lift design in the storage position with the actuator partially extended.

Figure 15 shows an Isometric view of the entire scissor lift preliminary design in the storage position. The parts list for each figure is on the following page. In this position the chair sits on the rails (part 9). This storage position will allow the design to be more compact than the previous design for storage. The supporting rod is the next part that will be explored to collapse for storage.

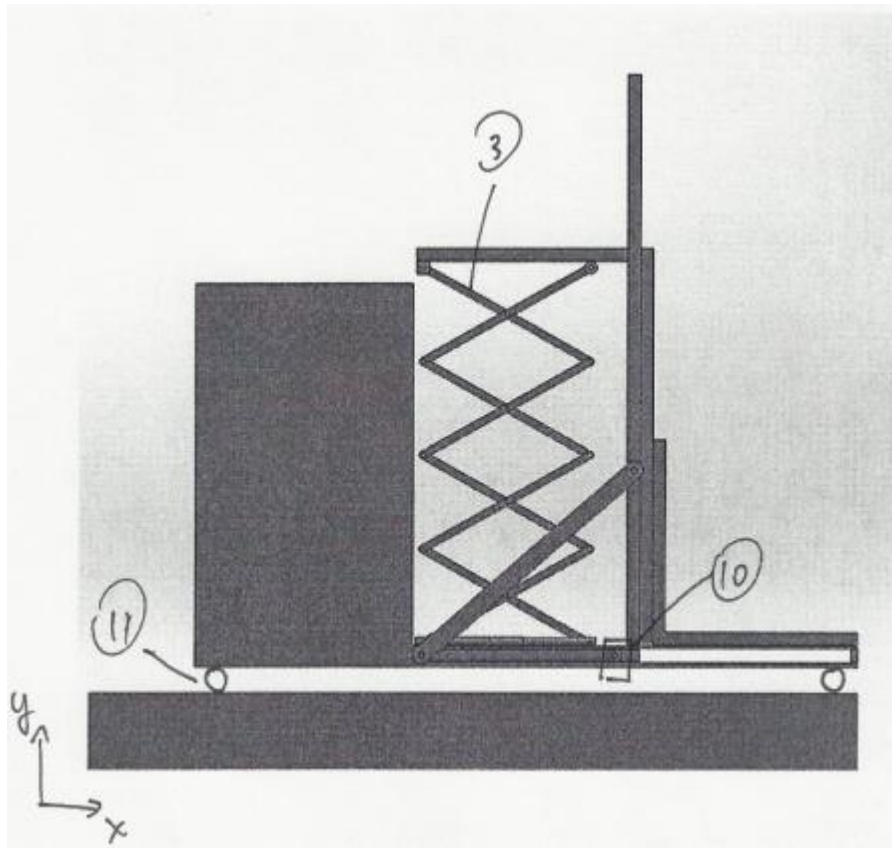


Figure 16: Side view of the scissor lift design in the storage position with the actuator partially extended.

Figure 16 shows a side view of the design in the storage position. In this view you can see how the chair rests on the rails and also the slider wheels in the slider link. The wheels are represented by part 11.

Parts List Table

1	Counter weight tank	7	Electronic Actuator
2	Top Chair Support	8	Supporting Link
3	Scissor Link	9	Rectangular Slot Rails
4	Supporting rod	10	Slider wheel
5	Chair Supporting Link	11	Supporting Wheels
6	Chair	12	Horizontal Scissor Link

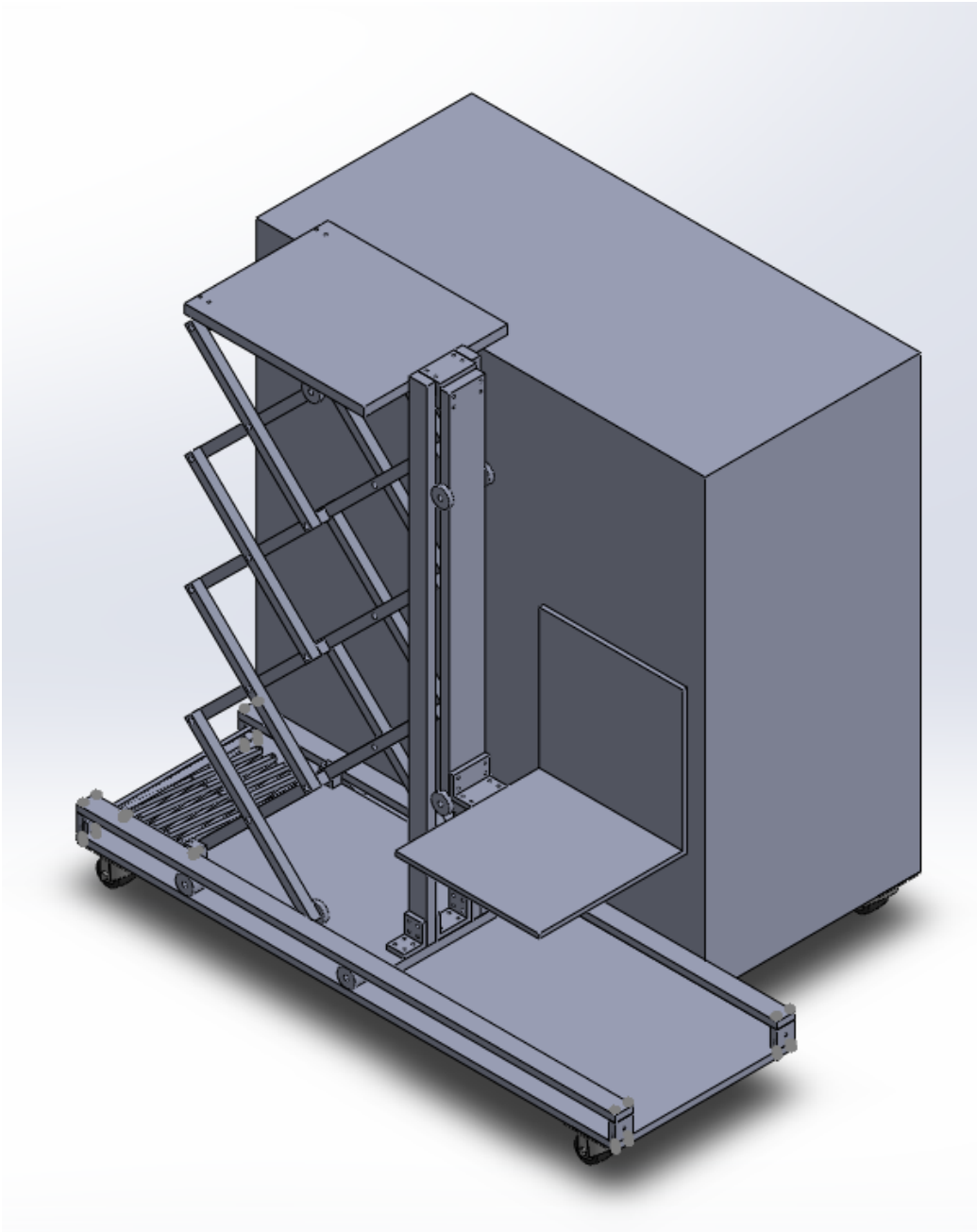


Figure 17: Scissor lift as it further developed in the loading position with the actuator fully retracted

This figure shows the evolution of the scissor lift. The chair is now positioned to allow the user to slide in from the side of the chair away from the edge of the pool. This was our last design before returning to a four bar linkage. The design chart is located in appendix A. the results of that design chart would indicate that the linkage rack chain scored the highest based on our criteria. After repeated attempts at revising each design the four bar linkage would be the most feasible.

Final design

Four-Bar Linkage Design

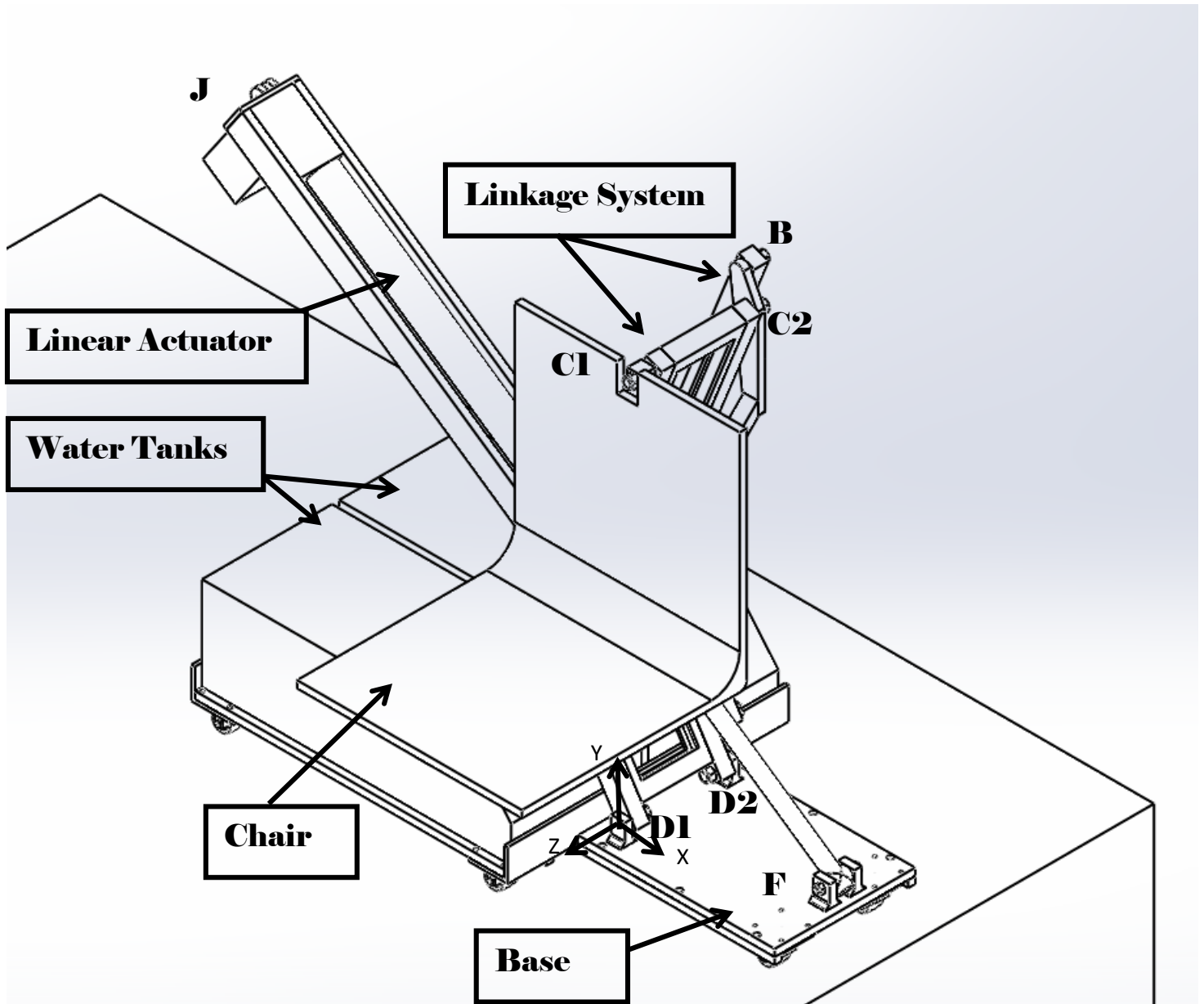


Figure 18: Isometric View of the four bar linkage with the actuator fully extended.

The team has chosen the alternative parallel four bar linkage as the main design because of the limitation of the two previous designs. The team had set out to reduce the motion of the user into the water and this design only has one rotation. The number of parts has also decreased from the two previous designs. The scissor lift and the straight line linkage design required two actuator motors to attempt to achieve the overall goal of placing the user into the water. This linkage requires only one actuator. The other two designs were really large. They would not have been easily stored. The scissor set is 73 inches tall and the straight line linkage failed to reach the desired depth required by the ADA standards. This design is also more simplistic than the

previous two complex designs. The following document has the graphical method used to create the full scale design, the kinematic analysis, exploded view of the parts, and the force calculations (this document contains only the drive link and actuator force). The design is actually a six bar because of the power source. The actuator is considered 2 links.

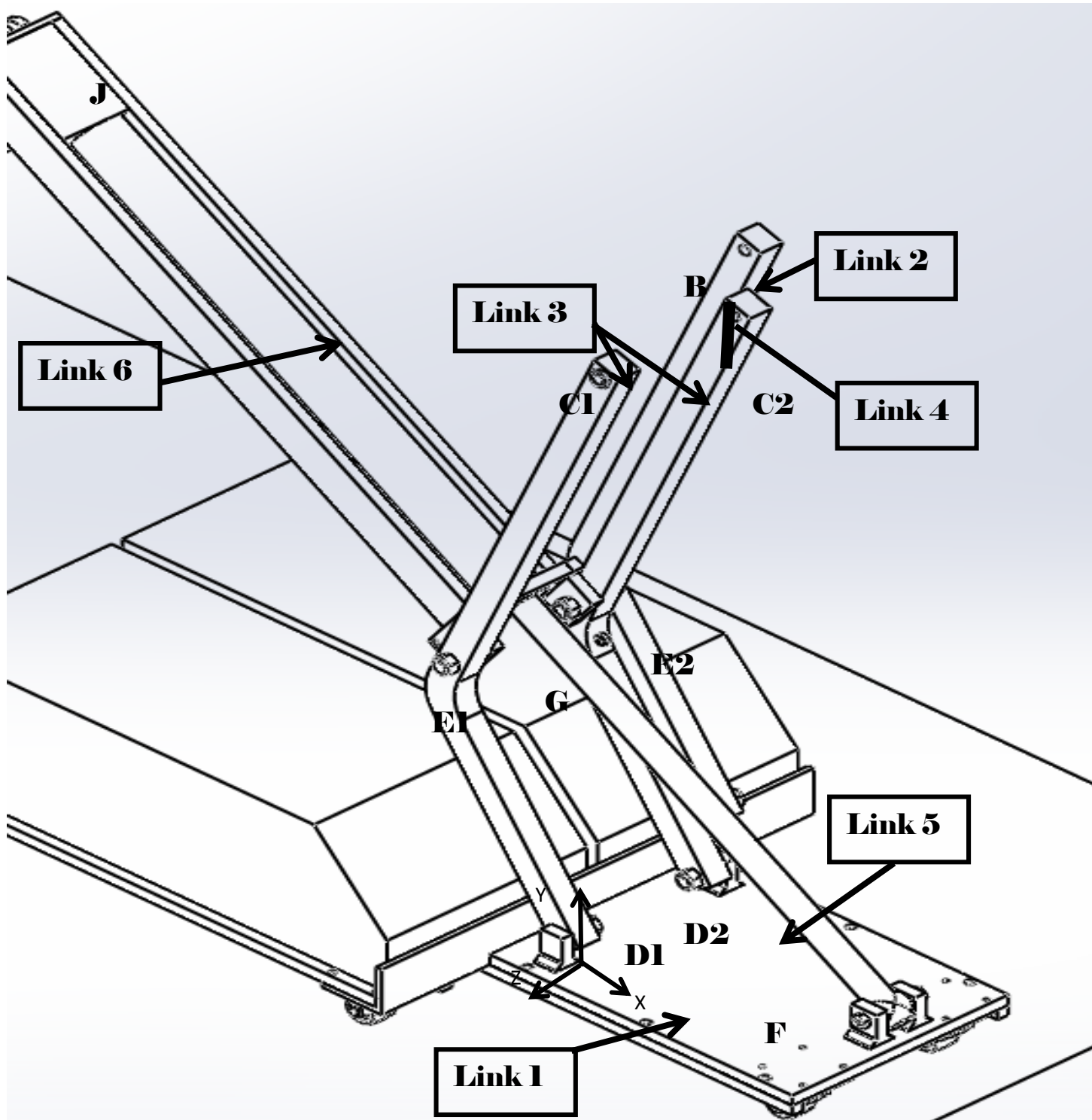


Figure 19: Isometric view of the design with out the chair showing the fourth kinematic link

Figure 19 shows a second isomeric view of the design without the chair. The view is meant to display the parallel four bar linkage system more clearly. The lower joints E and G are also more visible. The links are labeled to match the older documents. The joints and link numbers will be changed as requested. The iteration of this design has led to a significant reduction in bending moments of the supporting rod in joints C1 and C2.

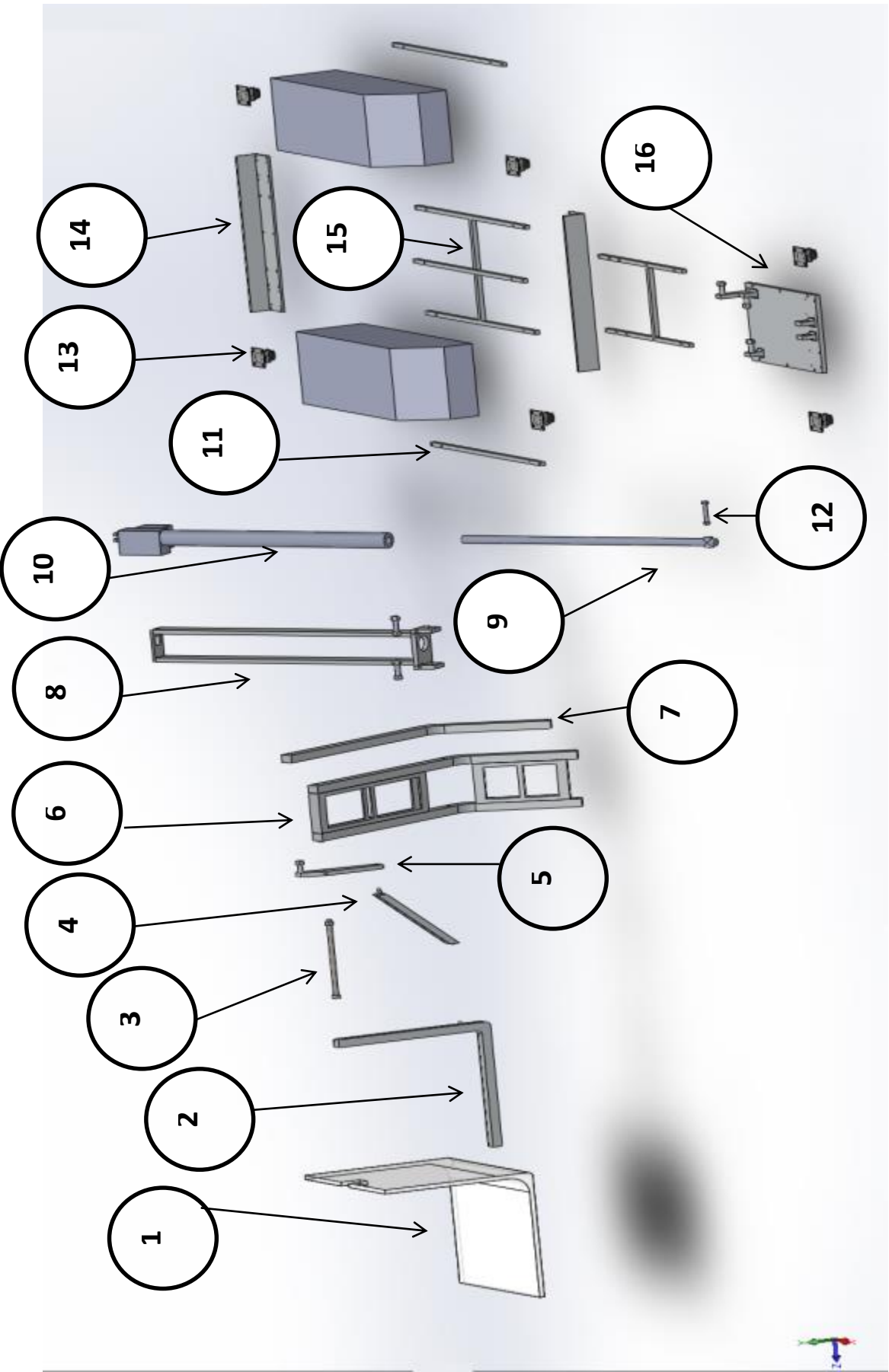


Figure 20: exploded isometric view of the entire design above with the parts list numbers followed by the parts list on page 25.

Part #	Description
1	Chair for the user to sit in
2	Chair bar that supports the chair along with the user
3	Main rod that connects kinematic links 2,3, and 4
4	Angled bar to support against the chair swinging
5	Straight rear supporting plate (kinematic link 4)
6	Main link responsible for movement of the chair (kinematic link 3)
7	(kinematic link 2) upper link for swing prevention
8	Actuator holder responsible for holding the linear actuator
9	Actuator piston that is to be push and pulled by the actuator cylinder (kinematic link 5)
10	Actuator cylinder that connects to the actuator piston (kinematic link 6)
11	Side bar for retaining the counterweights
12	Bolt 6x main bolts
13	Wheels for movement of the device
14	L shaped plate 2x for retaining the counterweight
15	Counterweight bar supports
16	Kinematic link 1 link base where kinematic links 2,3, and 5 attach

The parts list above reflects the parts in the figure 20 exploded isometric view of the entire design.

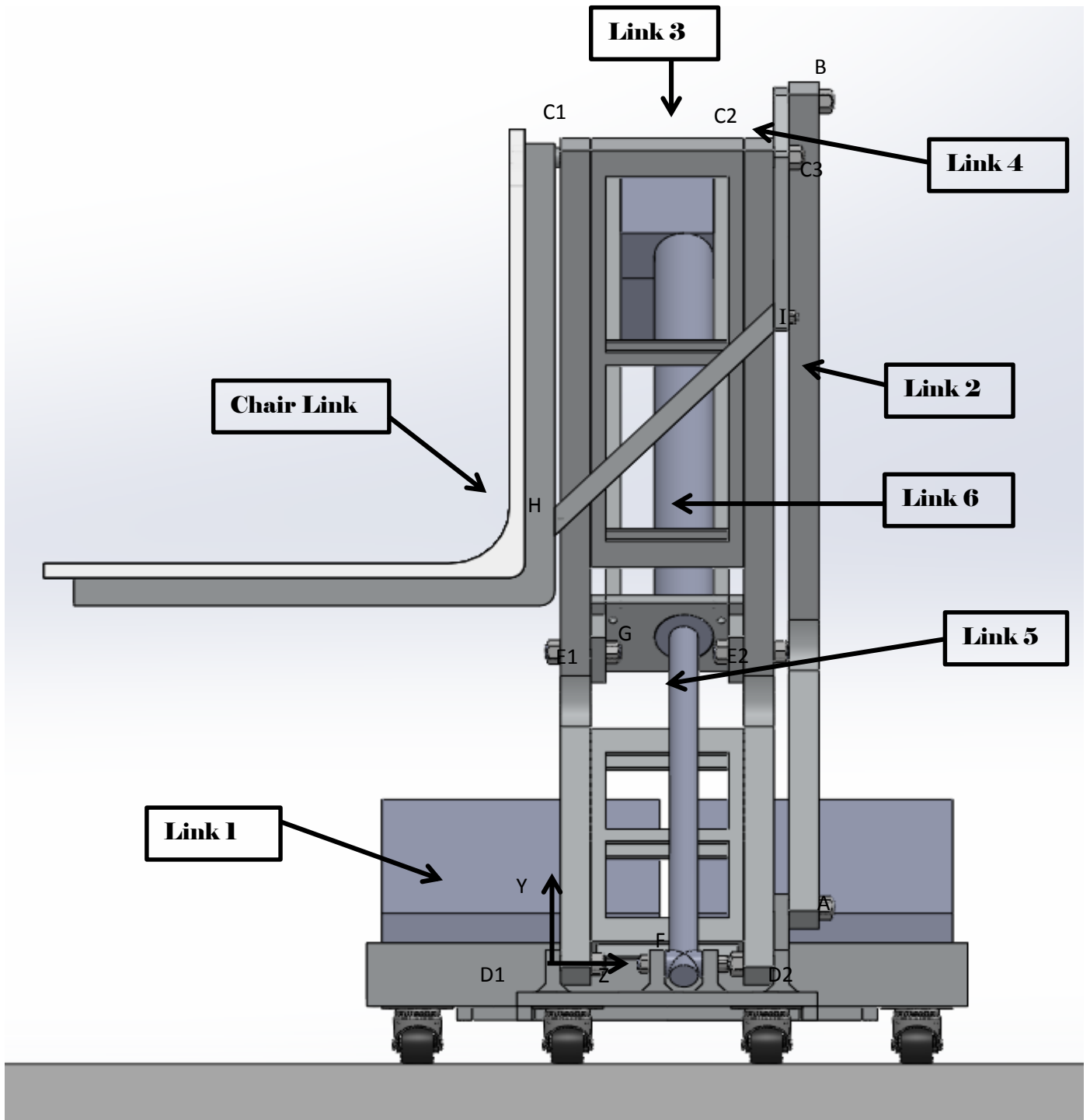


Figure 21: Front view of the chair with the actuator fully extended and the joints labeled.

Figure 21 shows the front view of the device in the (Z-Y) plane fully assembled with the actuator fully extended. The kinematic links are labeled in the front view as well. Link 4 (chair link) has the L-shaped beam rigidly connected to the rod. The rod extends from C1 through link 3 and link 4. The rod is secured by a nut at C3. Link 2 is pinned at B and A and secured with a nut. Link 3 is secured by a nut and is pinned at joints E1 and E2. The actuator was found to deliver a 0 force

not taking into account the weight of the actuator. This analysis includes the chair assembly, link 4, and link 2 in this document.

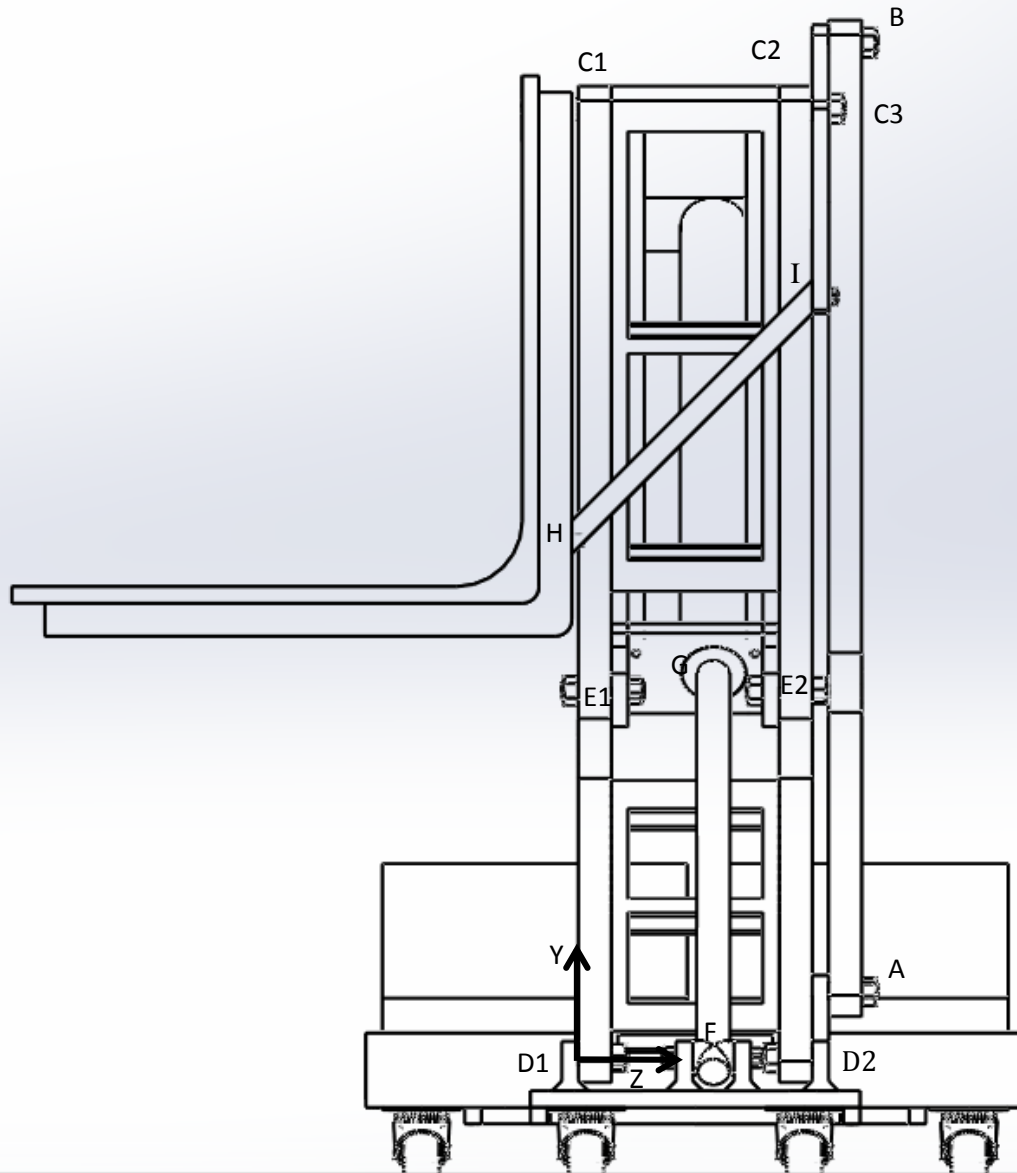


Figure 22: Non-Shaded Front view of the device with the actuator fully extended and the joints labeled

Figure 22 shows the non-shaded front view in the (Z-Y) plane of the device fully assembled with the actuator fully extended with the image not shaded. This view is meant to show the device in a different way to aid in clarifying the previous image.

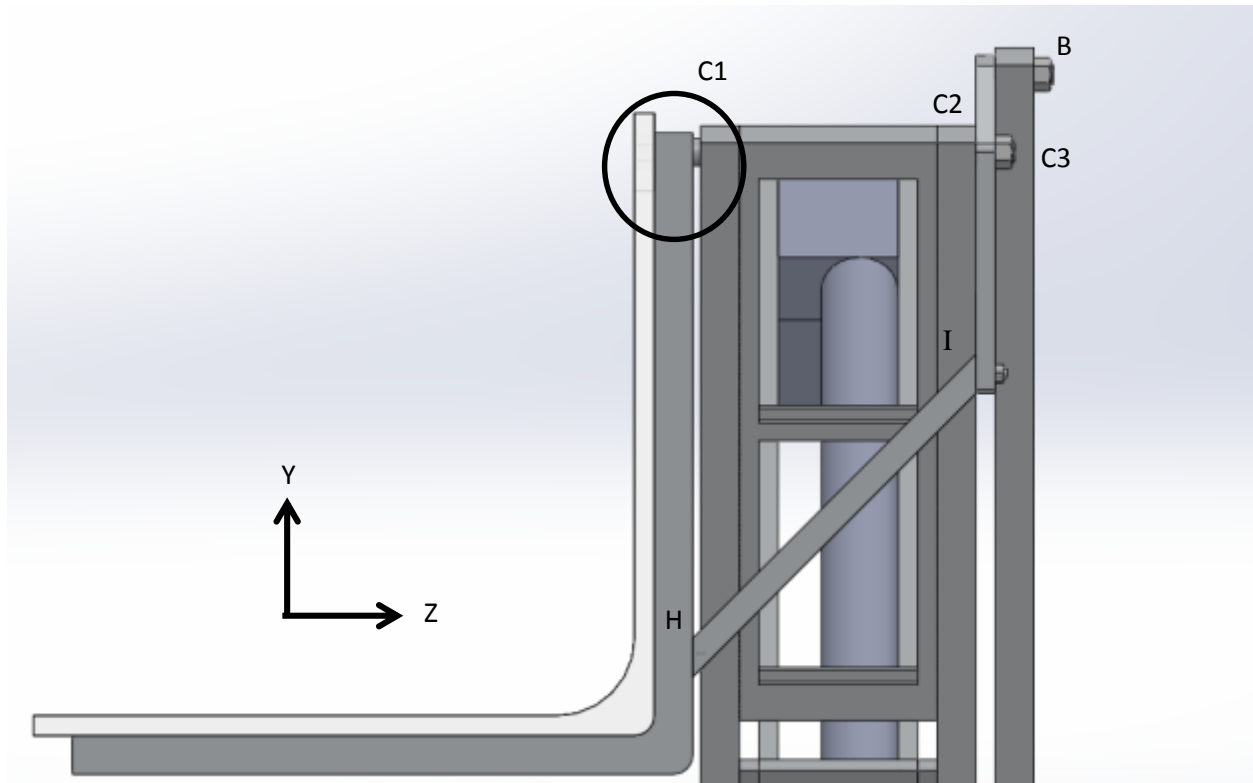


Figure 23: Front view of the device with the gap redesign.

Figure 23 shows the redesign of the rod so that link 3 is no longer in direct contact with the chair at C1. In the event that the chair rotates when the user sits in it the angled bar that is part of the chair support (link 4) is taking force. The chair will also rotate more easily around the rod with less friction.

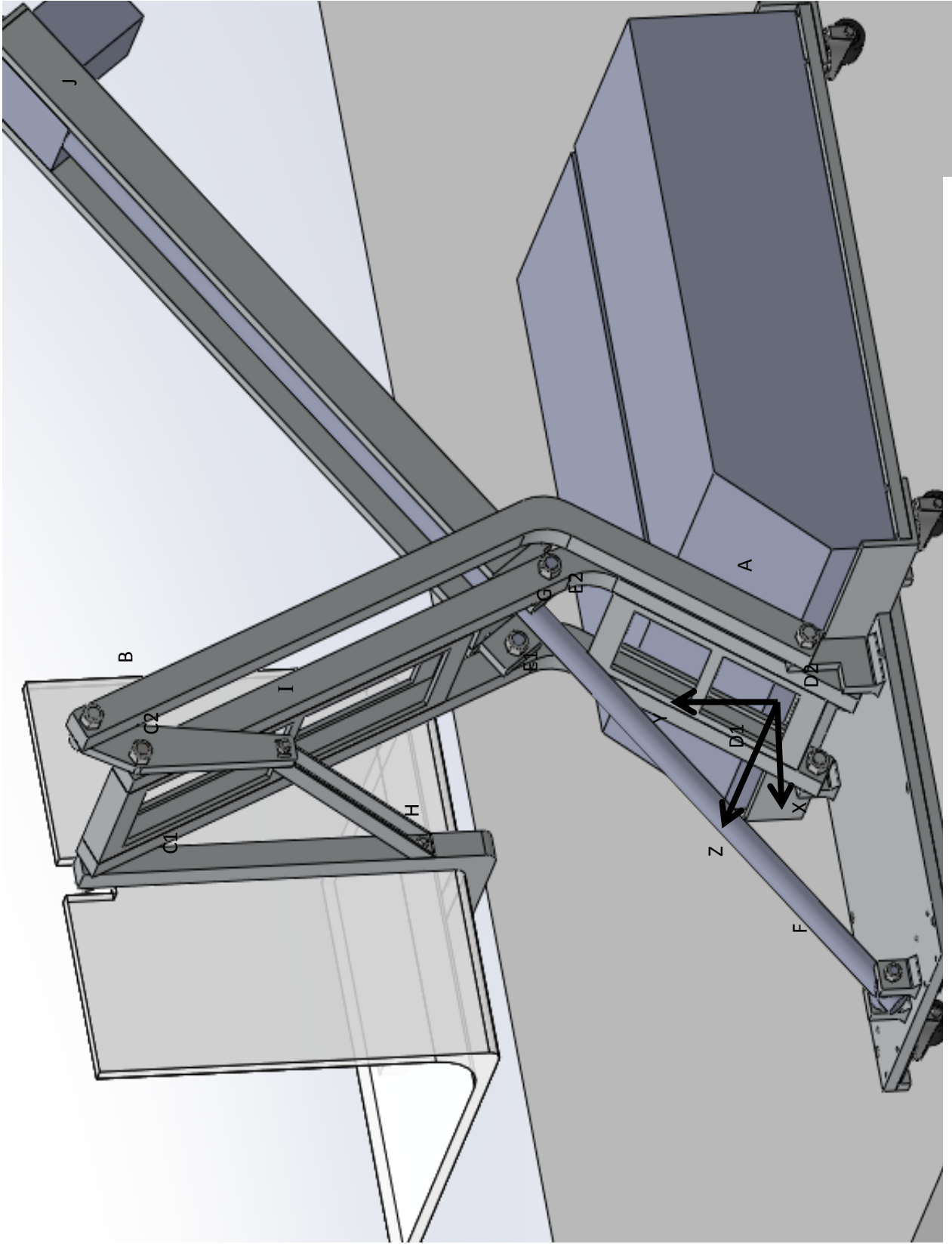


Figure 24: Rear Isometric view of the device with the actuator extended

Methodology

The design has been developed using the 2010 ADA standards for accessible design. The ADA standards indicate how far the center of the seat of chair should be from the pool, how high the seat of chair should be from pool deck, and how deep the seat of the chair should be submerged below water. This design was created using graphical linkage synthesis. The bars that connect the chair to the base were curved to achieve this motion.

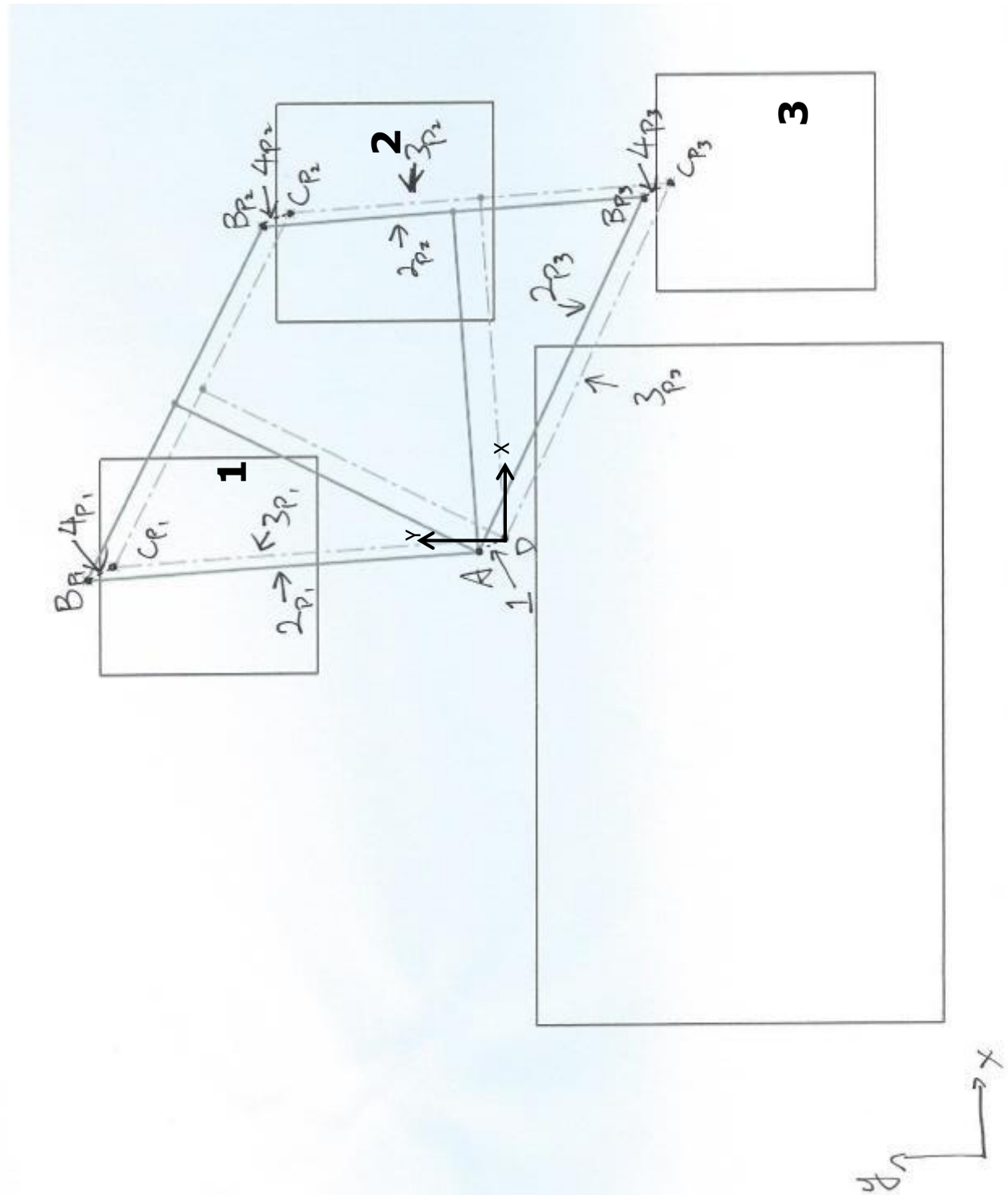


Figure 25: Three position synthesis used to create the linkage design in a side view.

Figure 25 shows the three positions (1, 2, and 3) used to create the design. Block 1, 2, and 3 are represented by the bold numbers and show the chair at three critical positions. Position 1 is the loading position for the user to enter the chair. Position 2 has the chair over the water just before being submerged. The final position 3 has the chair submerged below the water. The first two positions work well in moving the user from the deck over the pool. The final position 3 causes

the connecting links to pass through the pool deck. The chair at position 3 is critical in lower the user to the desired depth. The next step was to create links that could solve this problem. Each kinematic link is marked 1, 2, 3, and 4. Link 1 is the base and will not change position while the chair is in motion. The kinematic links 2 and 3 will move the chair (kinematic link 4) through the three positions. The links 2, 3, and 4 are marked by their number and position such as 2P1, 2P2, and 2P3. Link 4 will maintain it's orientation through each position to keep the user in the chair at a horizontal position through each step. The joints that connect each link to one another are labeled in a similar manner as the kinematic links such as BP1, BP2, and BP3.

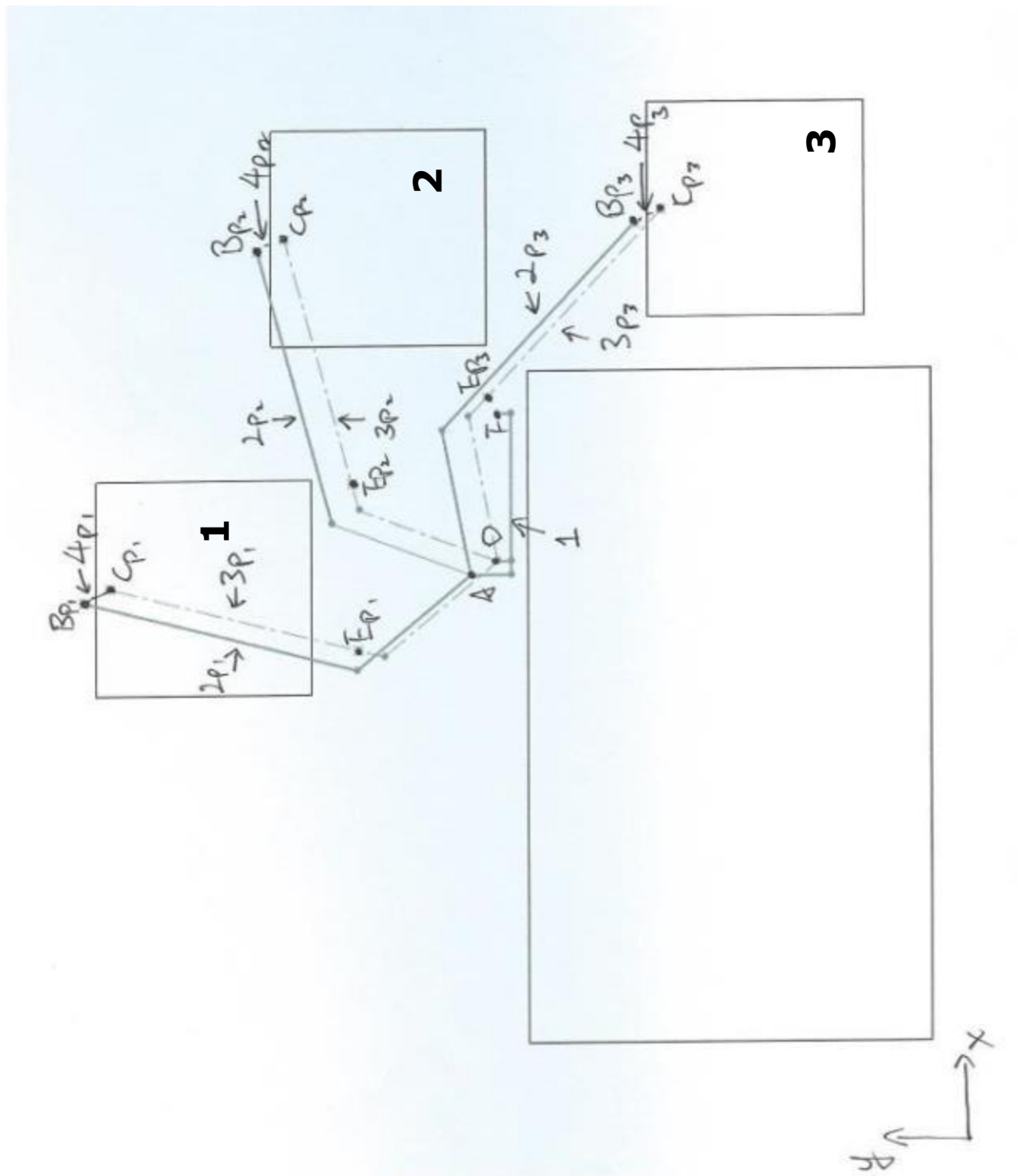


Figure 26: The graphical analysis of the two created links

Figure 26 shows the graphical analysis with two altered links. The kinematic links 2 and 3 are now curved links as a result of the graphical analysis. The curved links do not pass the pool deck and allow for the chair to reach the desired depth while simultaneously assuring that the chair stays horizontal. Joints A, B, C, D are considered moving rotating joints that allow links 2 and 3 to rotate

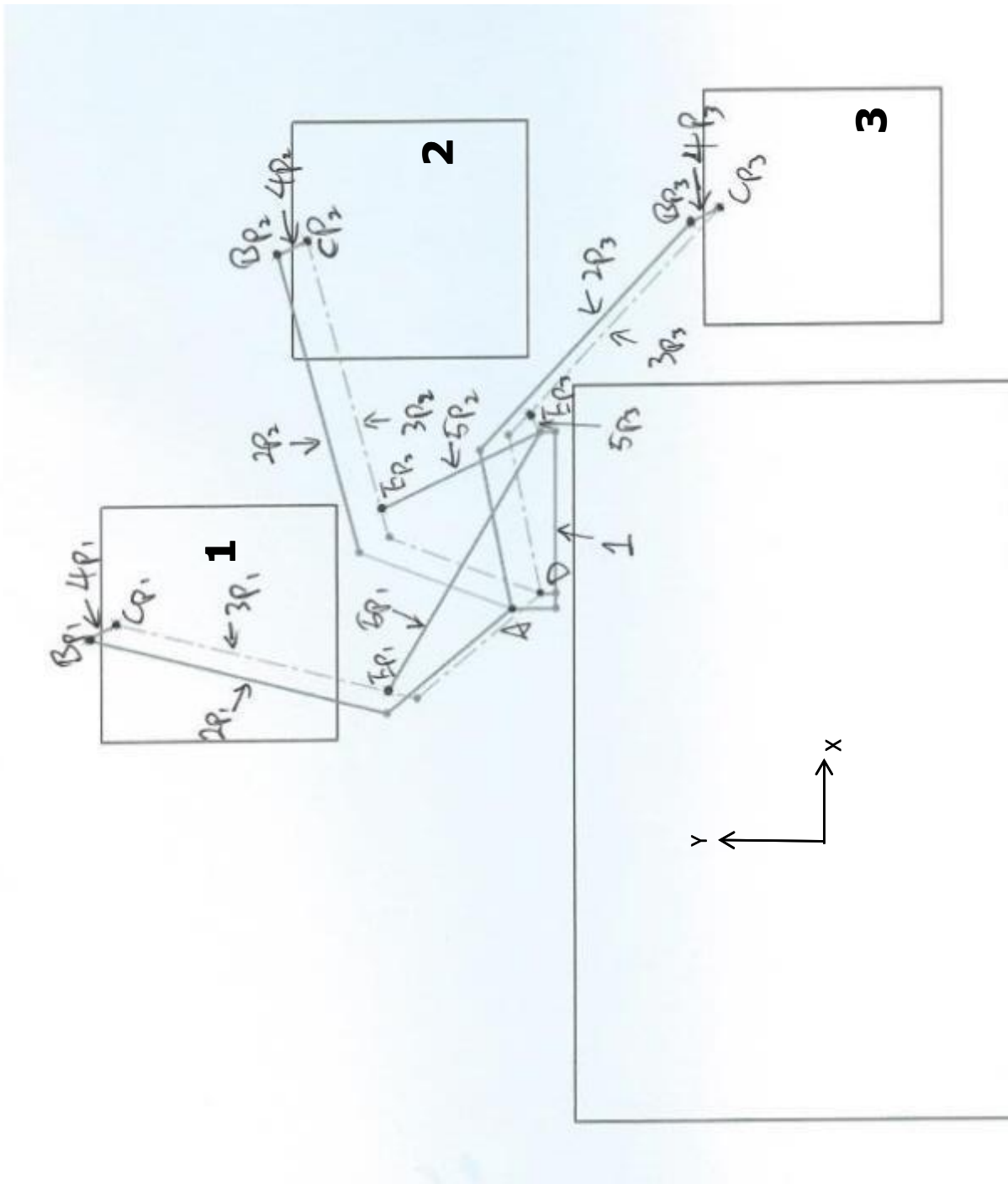


Figure 27: 3 position graphical Combined for position analysis.

Figure 27 represents the graphical analysis to include the position analysis for the electronic linear actuator piston. The actuator piston is labeled in this diagram as kinematic link 5. The actuator is considered two links. The cylinder of the actuator is omitted from this diagram. The actuator is pinned at joint F to link 1 and joint E represents where the piston cylinder connects. Joint E is a pin joint.

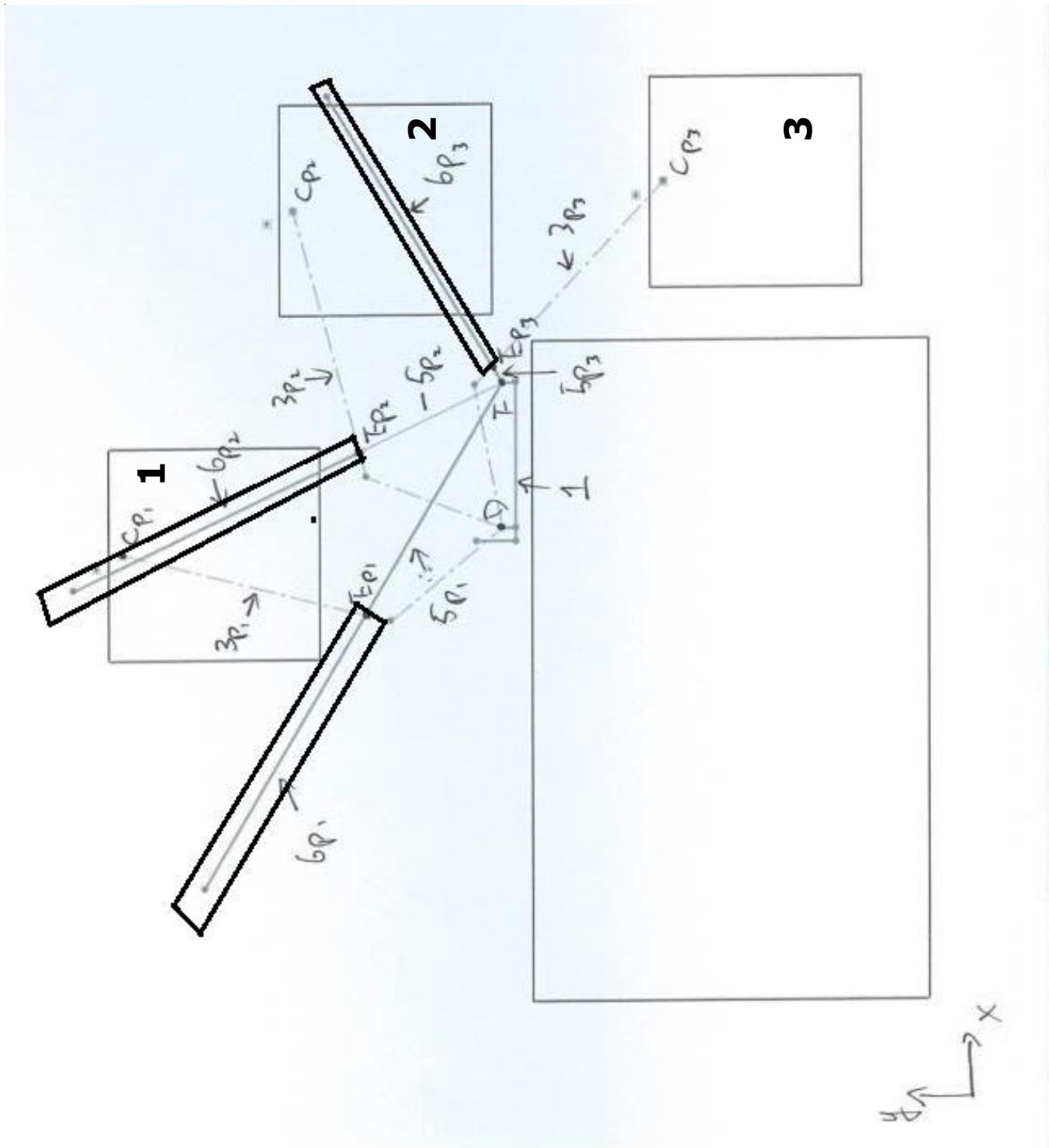


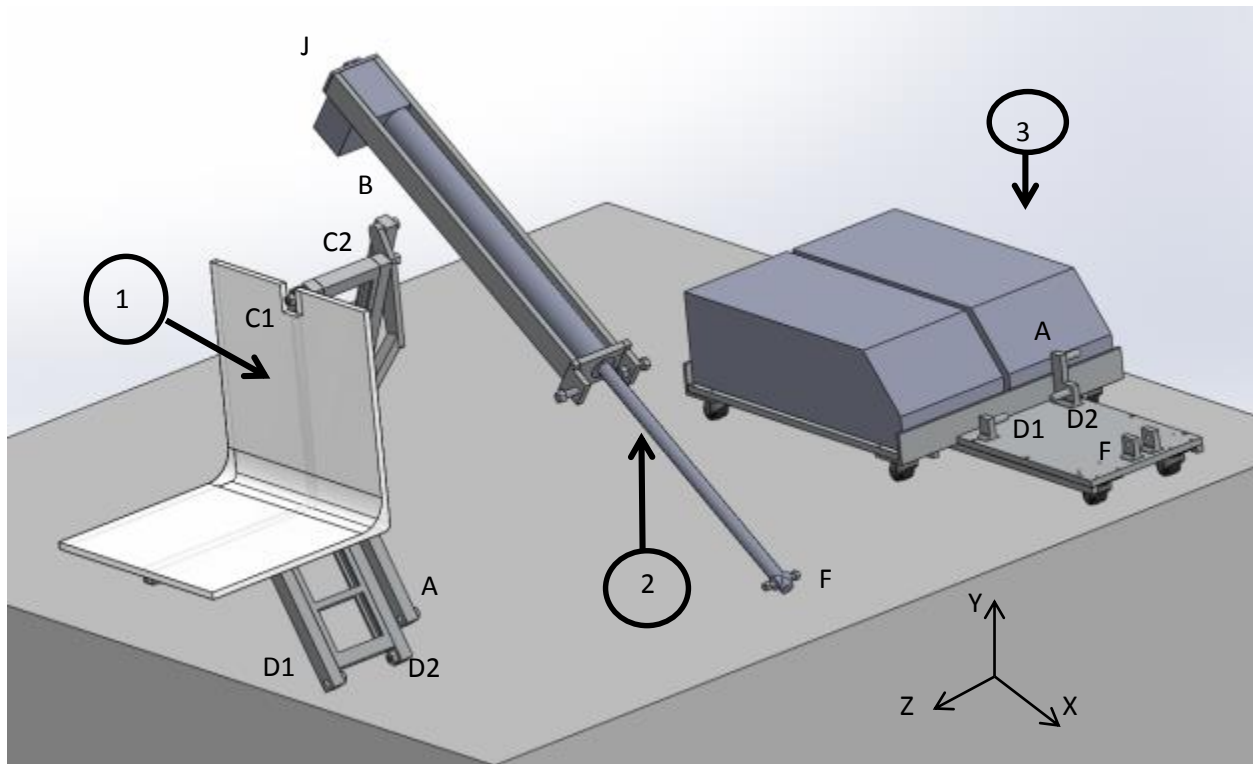
Figure 28: 3 position graphical analyses with the Actuator the user.

Figure 28 represents the graphical analysis of the device and included the actuator cylinder. The cylinder is labeled kinematic link 6. Link 5 will slide in and out of link 6 depending on the motion of the user. Figures 28 show linear actuator when it is fully extended and fully retracted. The 3-D representation of the device is shown in the next section. The next section will also better illustrate the parallel link 2b as seen in the joint and link chart presented below.

Table 3: Joints Table from the exploded views that shows a visual on how each link connects and where each joint connect.

Link 1(ground link)	A pin joint		Link 3(lower curved link)	E pin Joint
Link 2(Upper curved link)	B pin joint		Link 1(ground link)	
Link 4(Chair Link)	C pin joint		Link 3(lower curved link)	G slider link
Link 3(lower curved link)	E pin joint		Link 4 (chair link)	
Link 6(Actuator Cylinder)	F pin joint			
Link 1(Ground link)	I pin joint			
Link 3b(parallel curved link)	H pin joint			
Link 6 (Actuator Cylinder)				

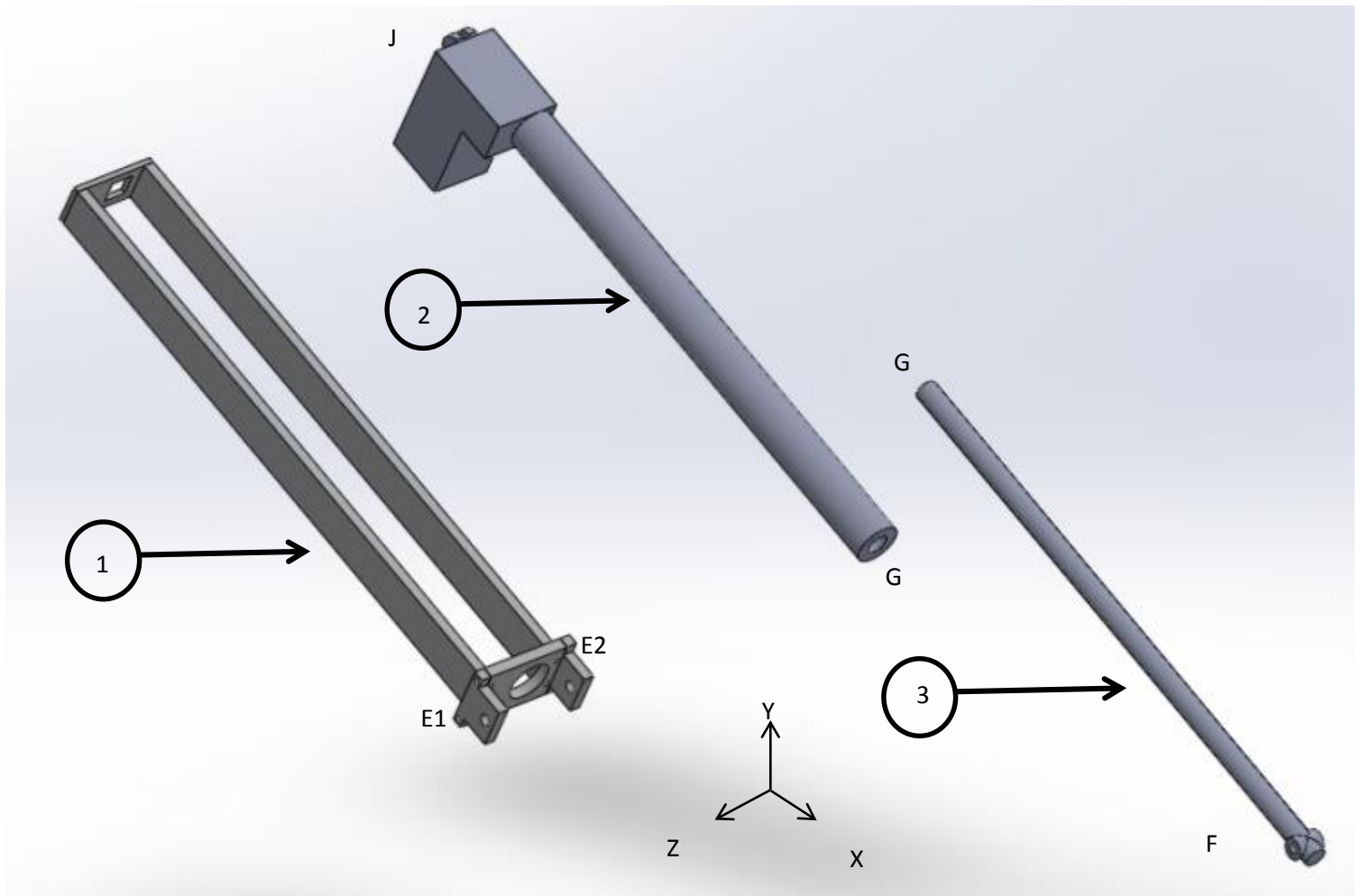
Exploded views



1	Chair Assembly
2	Actuator Assembly
3	Base Assembly

Figure 29: The 3 main assemblies of the device in an exploded isometric view

Figure 29 shows the exploded isometric view of the design. The parts list is below the image and the joints list is located in table 3 on page 36. The main parts of the design are the linkage system in the chair assembly (kinematic links 2, 3, 4), the linear actuator (kinematic links 5 and 6), and the base (kinematic link1). Each assembly attaches at their respective joints indicated by letter such as joint A connects to A.



1	Actuator holder
2	Actuator cylinder
3	Actuator piston

Figure 30: Exploded view of the actuator and holder

Figure 30 shows this exploded view of the actuator holder along with the actuator. The holder for the actuator allows for a direct connection to the lowered curved links to drive the chair through the desired motions. The actuator is broken into its main parts, the cylinder and the piston. The piston for this design is an electric DC linear actuator powered by a battery. The battery is not shown but will be attached to the base. The part list is below the figure and the joints table is located on page 36.



1	Upper holder plate
2	Side parallel plate
3	Small holed parallel plate
4	Bottom plate

Figure 31: Exploded view of the actuator holder

Figure 31 shows this exploded view of the actuator holder. The holder for the actuator allows for a direct connection to the lowered curved links to drive the chair through the desired motions. The part list is below the figure and the joints table is located on page 36. Though the holster is an assembly of parts it is considered rigid to the actuator for the analysis of the design.

1	Base(Kinematic link 1)	4	Rear rectangular rods
2	Front rectangular rods	5	Counterweight
3	Wheels	6	L-shaped bracket

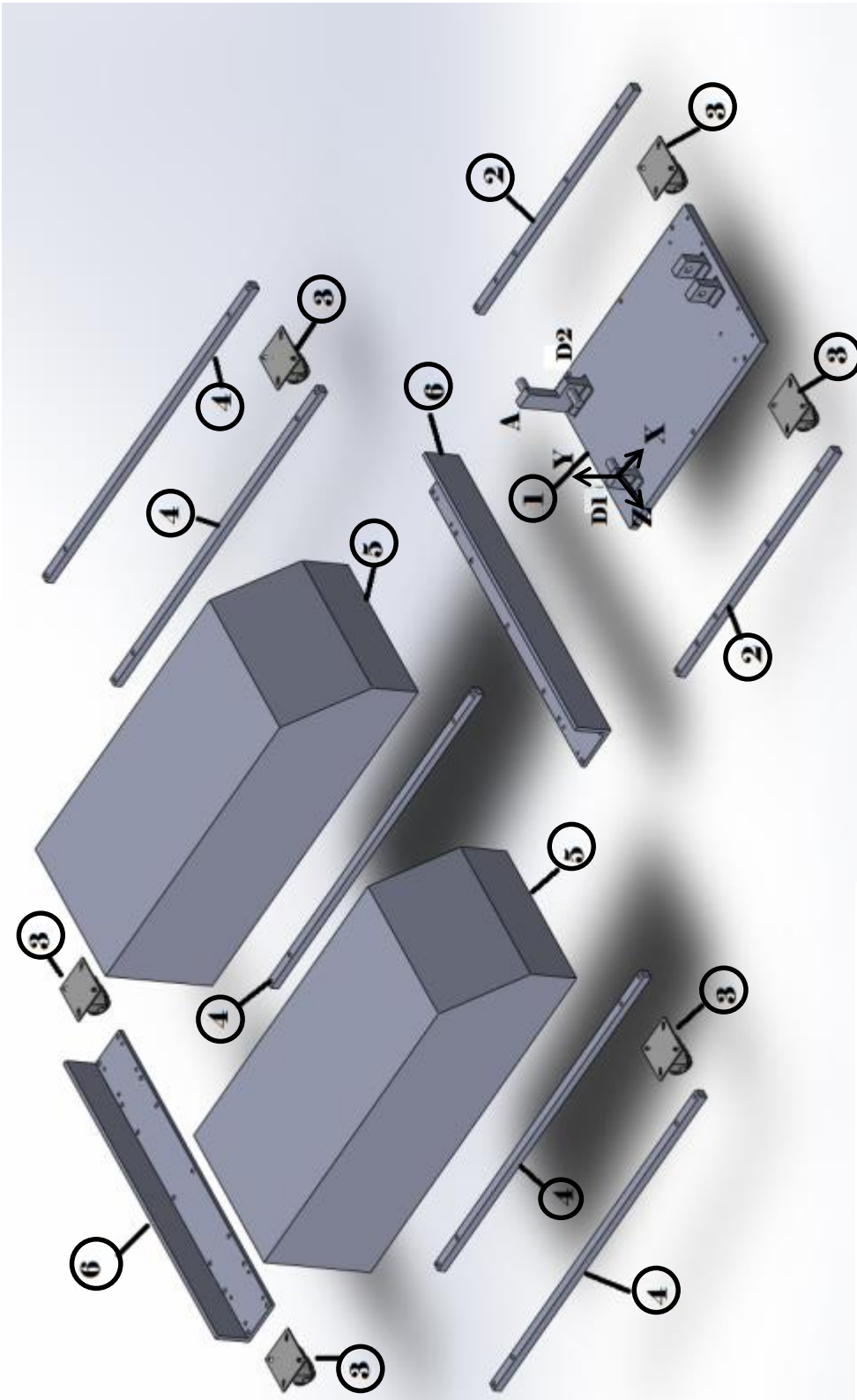


Figure 32: Exploded view of the base

Figure 32 shows this exploded view of the Base that supports the four bar and the counterweights. There are 6 wheels for balance. There are 7 support rods. The ground link

supports the curved links. The Base (part 1) will be pinned to the actuator at joint F to keep it in place on the base. The part list is below the figure and the joints table is located on page 36.

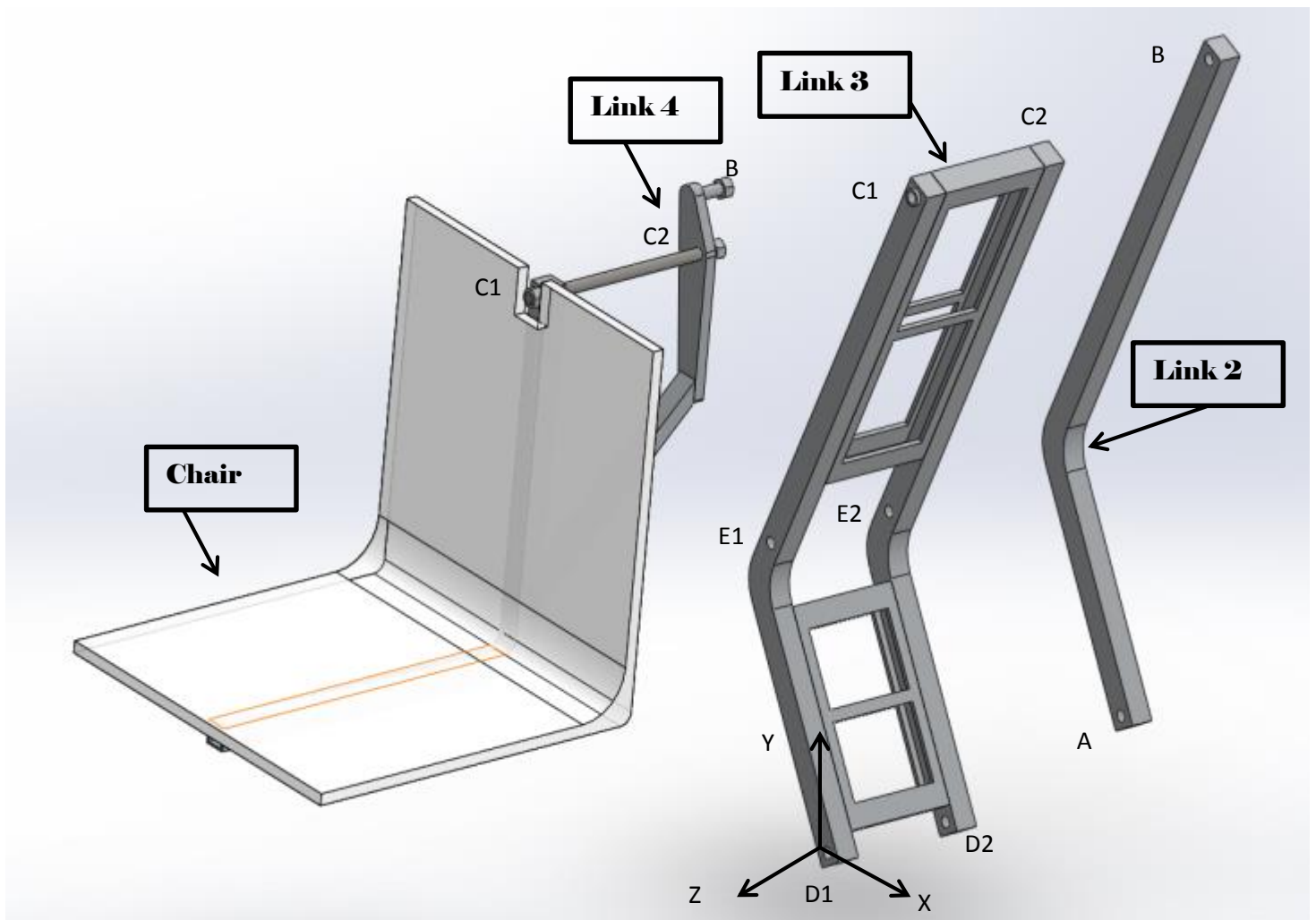
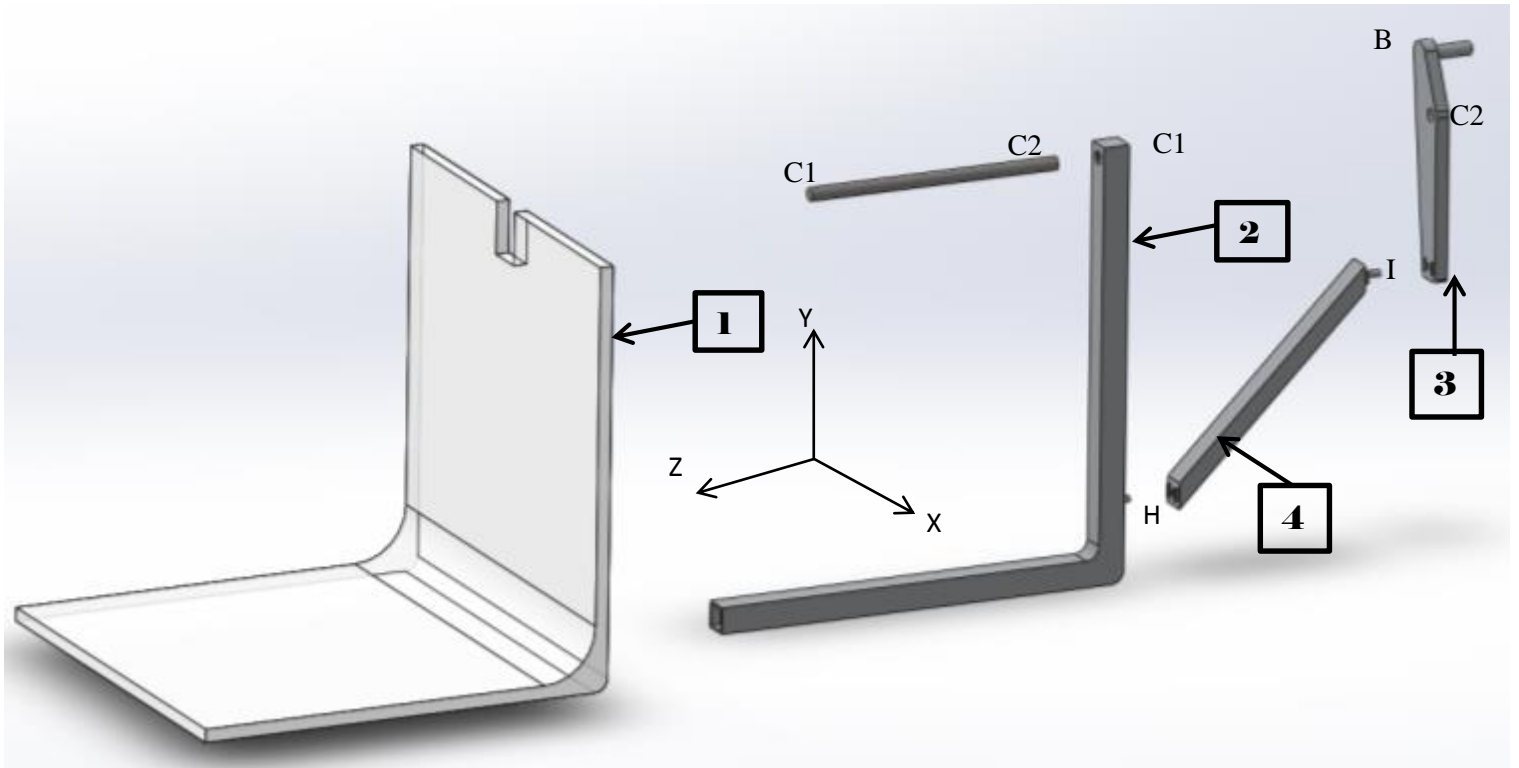


Figure 33: Exploded isometric view of the linkage system

Figure 33 shows the linkage system in an isometric exploded view with the curved links that support the chair link. The chair is partially assembled. The kinematics links 2 & 3 as seen in figure 33 complete the assembly as seen in figure. The lower curved bars connect the actuator to the chair and the base. The upper bar (link 2) will act as a support against swinging in the positive or negative x direction. The direction of the support depends. The rectangular bars in the middle of link 3 are meant to keep the curved links together and limit the bending of the rod. The part list is below the figure and the joints table is located on page 36.



1	Chair
2	L shaped support rod
3	Chair support vertical
4	Angled Chair support

Figure 34: Exploded view of the chair link 4.

Figure 34 shows this exploded view of the chair link. Part 2 supports the chair and take the bending while the support (part 3) reduces the moment created by the user.

Position analysis

Kinematic Analysis

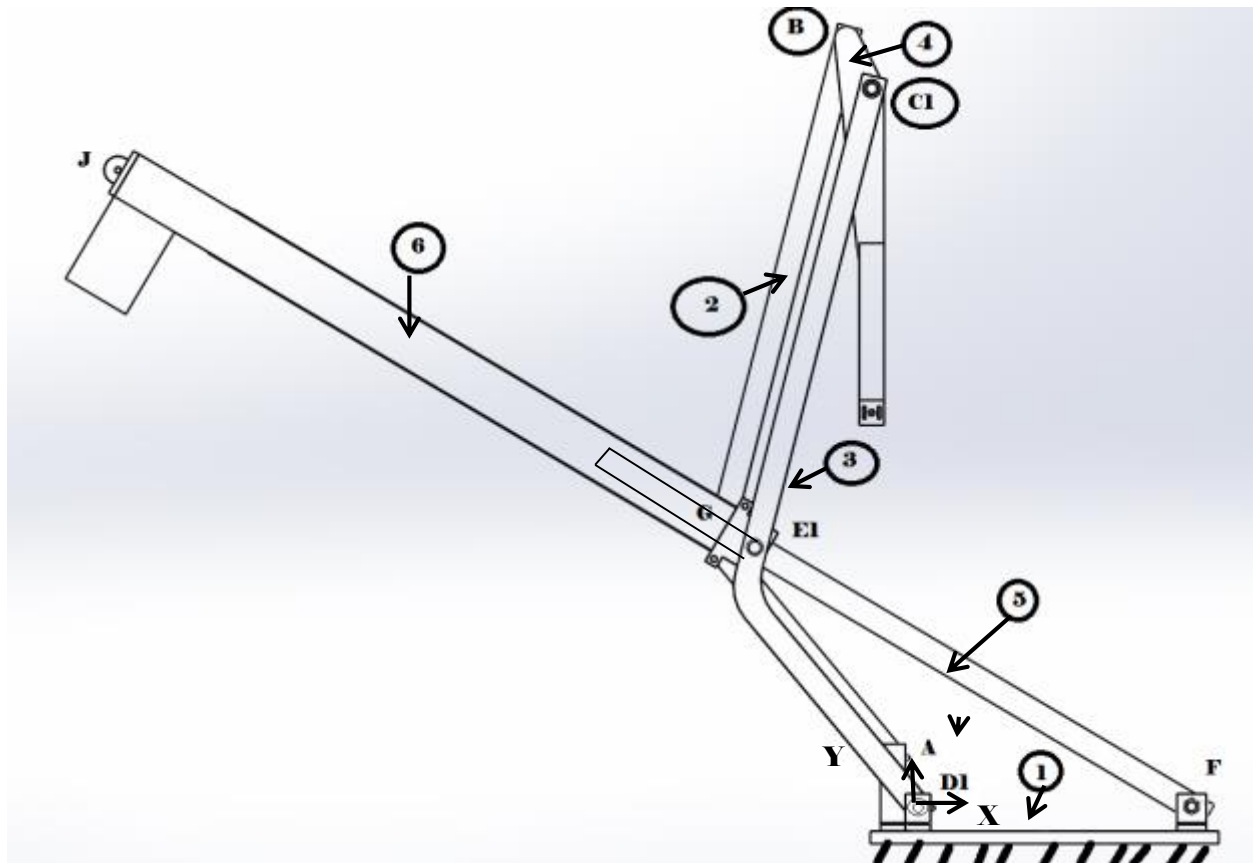


Figure 35: (X-Y) plane-(Side view) of the design with the actuator fully extended.

Figure 35 shows the design with the actuator almost fully extended. The actuator has been connected to the bottom curved link in order to move the chair through the three positions indicated previously. The actuator here is extended to its necessary position for the chair's seat height. The position analysis done for the design yielded critical information in the force analysis. There are 20 different positions used for the analysis. The most important a part of the position analysis are the transmission angles and the angles that the curved links (link 2 and 3) make with the chair link 4. The angles for that transmission angles can be observed in the position analysis in Appendix B. The position analysis revealed the locations where the forces will alternate between pulling and pushing the actuator piston when the user is being lowered into the water from the starting position with the actuator fully extended. When the joint (D) falls beneath the joint (E) the actuator takes on its largest forces with small changes in displacement. Research shows the ideal transmission angles for the actuator would be around 90 degrees. The transmission angles for the design are reasonable by comparison. The angles range from 73-110 degrees. The transmission chart is located in the appendix A. All of the graphs for the kinematic analysis are in the Appendix B. Table 4 is meant to show the trend relative to the stroke length of

the actuator as it moves from being fully extended to fully retracted. The power that is transmitted to link 3 is going to be tangent to the link itself.

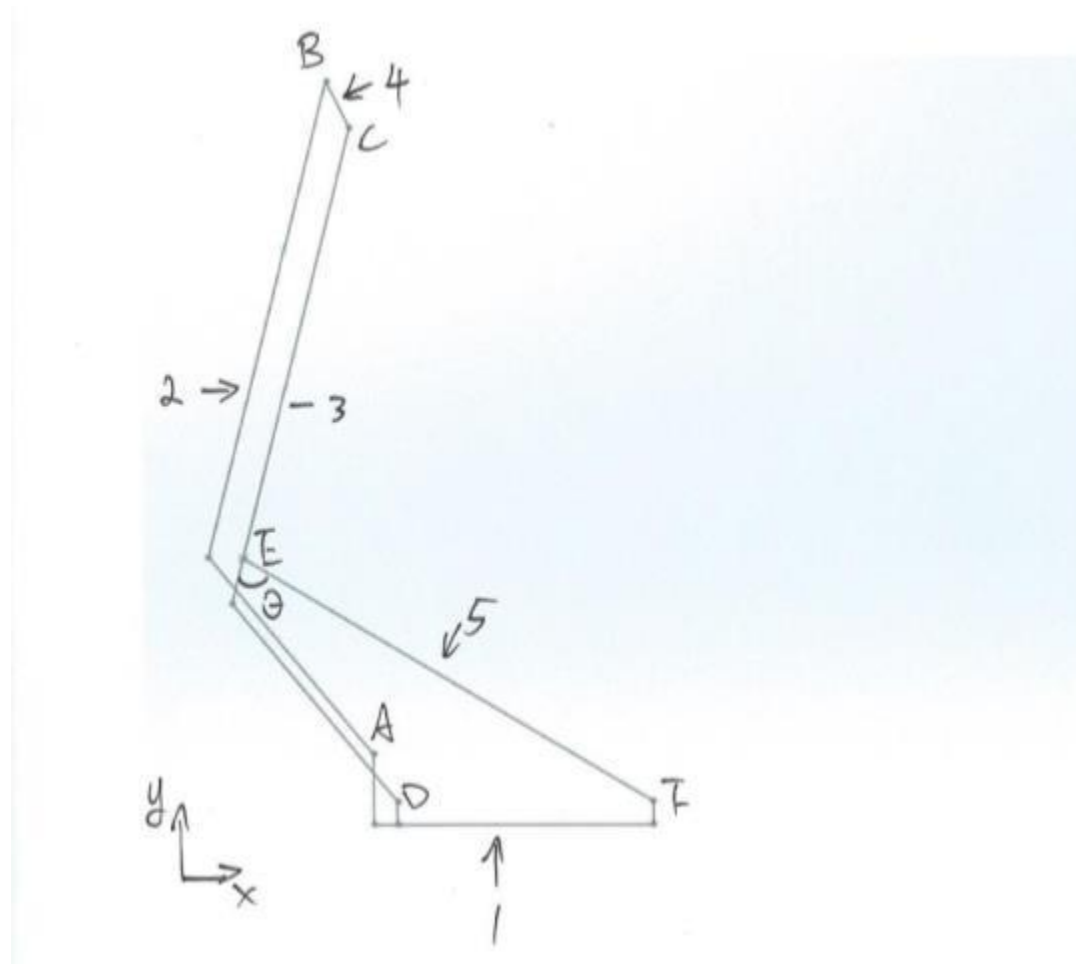


Figure 36: kinematic drawing of the links with the actuator fully extended

Figure 36 shows the kinematic drawing with the actuator when the actuator is fully extended. The number 1 in figure 36 represents the ground link. The number 4 represent the chair link that is to be moved. The number 2 represents the top curved link that connects the chair to link 1 with two pin joints located at each end of link 2. The number 3 represent the second curved link that connects the chair back to link 1. The number 5 represents the actuator that moves the chair through it three positions. The transmission angle shown (ω) is between the actuator and link 3. The actuator cylinder is collinear to the actuator piston and is omitted in this figure.

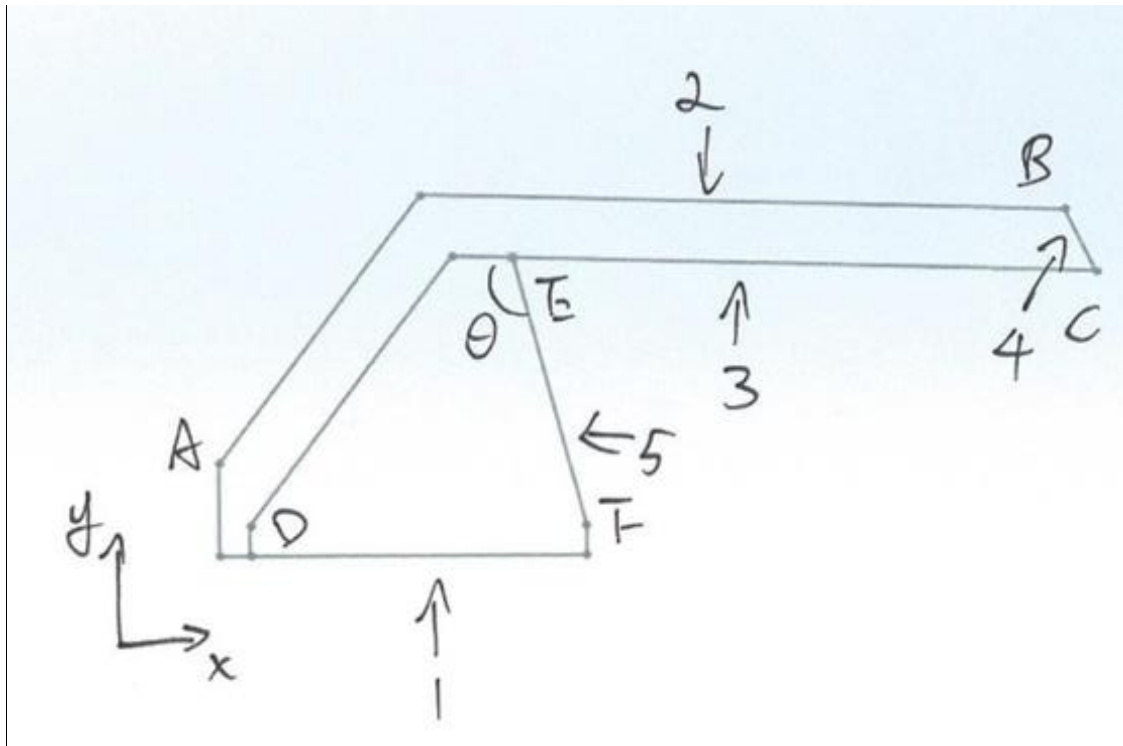
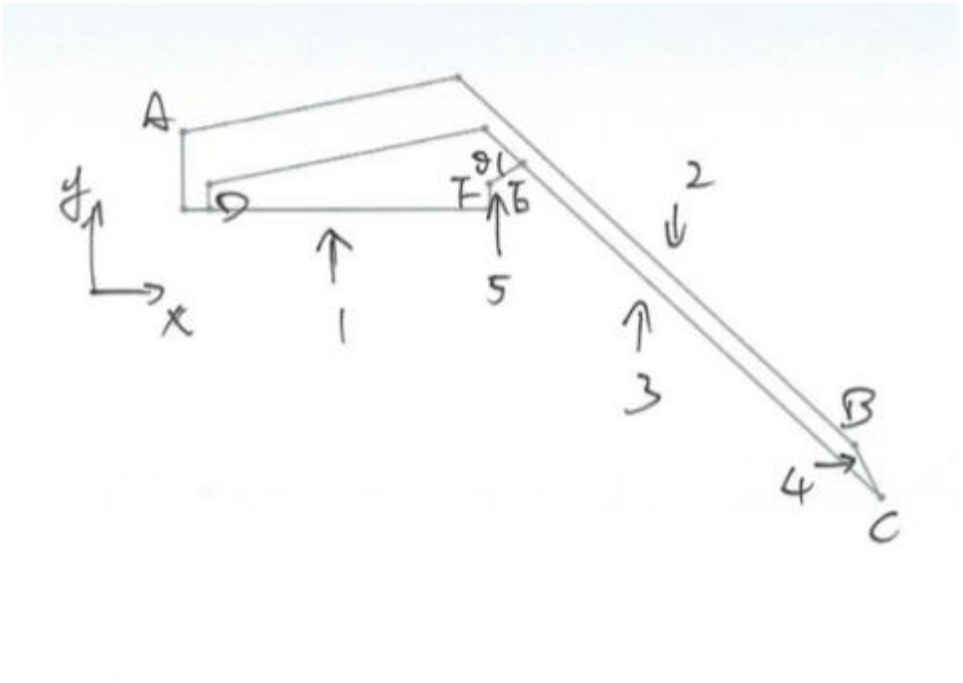


Figure 37: kinematic drawings of the links in intermediate position with the chair entering or exiting the water..

Figure 37 shows the device with the actuator just before the chair is about to be fully submerged (right). The actuator has been connected to the bottom curved link in order to move the chair through the three positions indicated previously. The number 1 in figure 37 represents the ground link. The number 4 represent the chair link that is to be moved. The number 2 represents the top curved link that connects the chair to link 1 with two pin joints located at each end of link 2. The number 3 represent the second curved link that connects the chair back to link 1. The number 5 represents the actuator that moves the chair through it three positions. The transmission angle shown (ω) at joint location (E) is between the actuator and link 3.



En

Figure 38: Kinematic drawing of design when the actuator fully retracted

Figure 38 shows the kinematic drawing with the actuator when the chair is submerged into the water. The number 1 in figure 20 represents the ground link. The number 4 represent the chair link that is to be moved. The number 2 represents the top curved link that connects the chair to link 1 with two pin joints located at each end of link 2. The number 3 represent the second curved link that connects the chair back to link 1. The number 5 represents the actuator that moves the chair through it three positions. The transmission angle shown (ω) is between the actuator and link 3 (shown at joint location E).

Transmission angle theta

The transmission angles were the one of the many driving forces that led to the optimization of the four bar design. The transmission angles are used to judge initial quality of the force and velocity at the joint where the actuator connects to the lower curved bar that raises and lowers the chair in and out of the water. The transmission angle for the design is taken between the actuator and the lower curved link as illustrated in figures (36, 37, and 38). The transmission angles for the design range from 73 degrees to 110 degrees. In the loading position the transmission angle is 73 degrees, 100 degrees at the water level, and 74 degree in the submerged position.

Safety factor

The safety factor for the design was chosen prior to the stress analysis at 3 because of the human factor. The safety factor was used to guide the design. The design has been updated based on the findings of the stress calculations.

Force and Stress Analysis

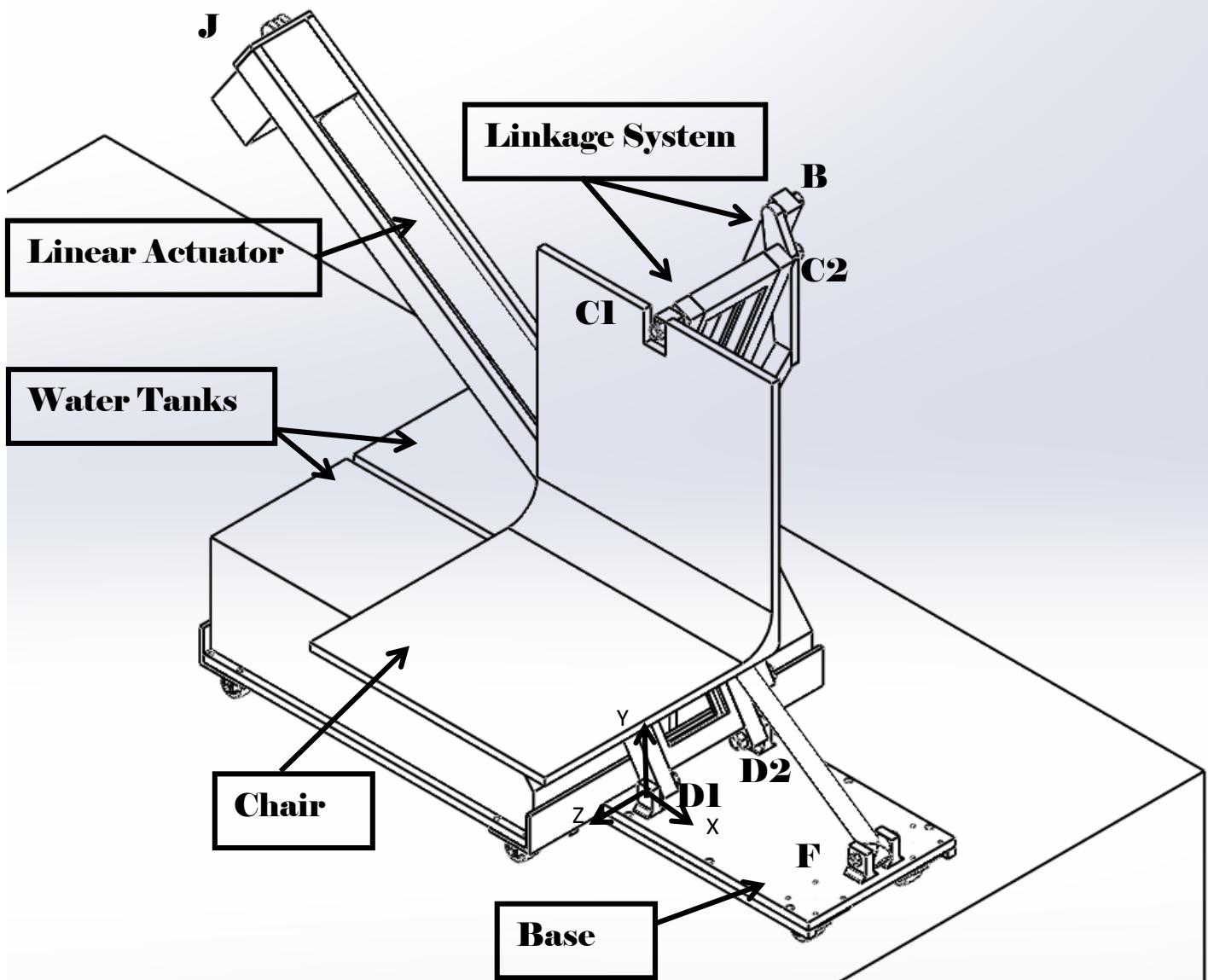


Figure 39: Isometric View of the four bar linkage with the actuator fully extended.

The following section is the combined force and stress analysis of all the major part of the design. Each design analysis will have a 3d visual aid followed by the FBD of the force analysis and then the stress analysis.

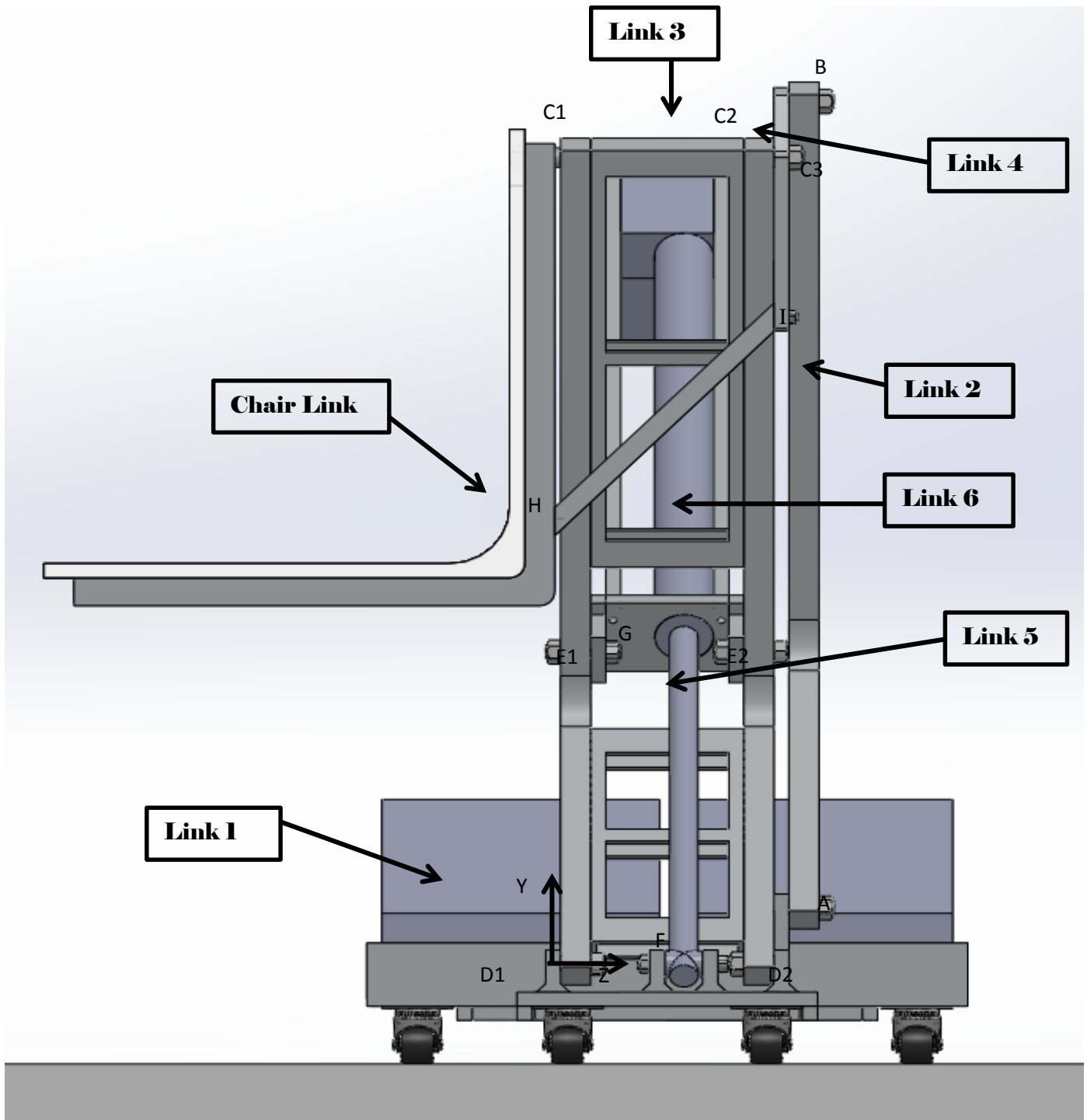
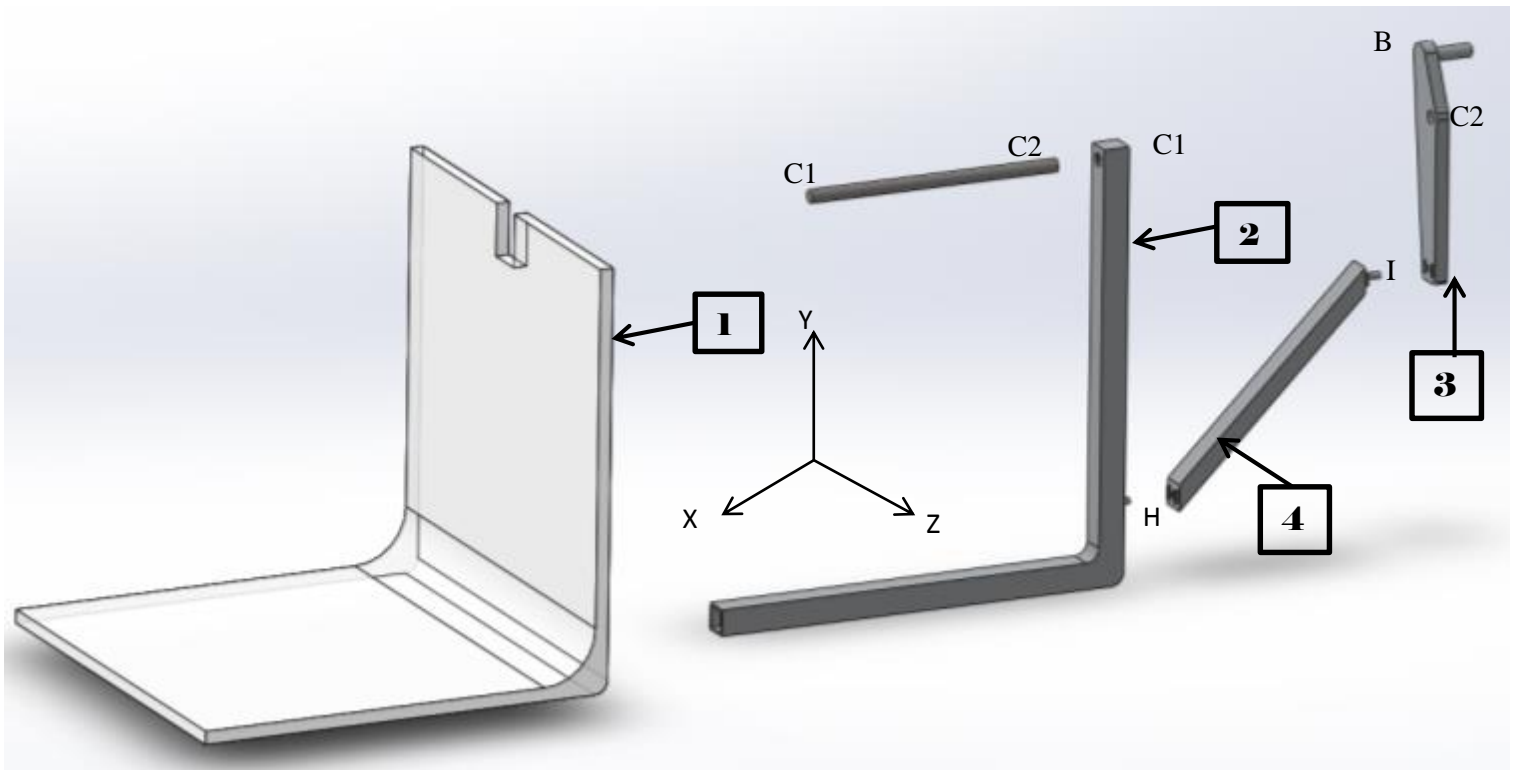


Figure 40: Front view of the chair with the actuator fully extended and the joints labeled.

The force analysis for the final design was first conducted in the X-Y plane. The chair was analyzed first. The weight from the user is concentrated in the center of the chair as seen in (Figure 40). The results of the forces are in appendix (C) tables (3-4) on page 99. In the first case scenario the user's weight will be supported by the rod at the joint location (C1). The assumption here is: **The rod at location C1 as seen in (Figure 40) has an ultimate strength that will**

support the user's weight and that the rod will not fail by compression (bearing stress) or tear out of the material. The resulting free body diagram is seen in (Figure 43) on page (51).

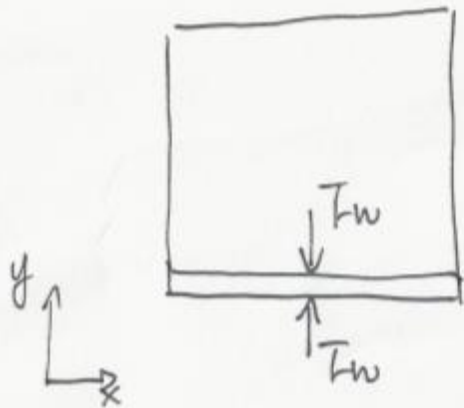


1	Chair
2	L shaped support rod
3	Chair support vertical
4	Angled Chair support

Figure 41: Exploded view of the chair link 4.

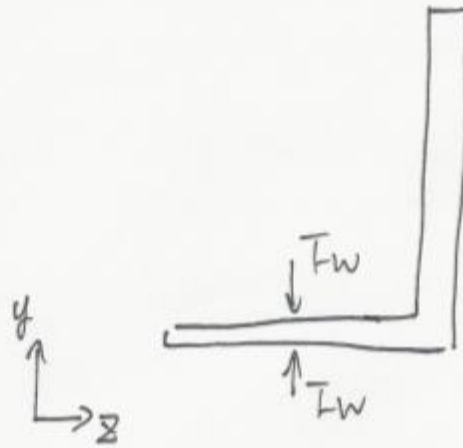
Chair:

x-y plane.



$$\sum T_{y20}: T_w = T_w$$

y-z plane



$$\sum T_{y20}: T_w = T_w$$

Figure 42: Free body diagrams for the chair in the X-Y and Z-Y planes.

Figure 42 shows the free body diagram of just the chair. The results of the forces are on page 99.

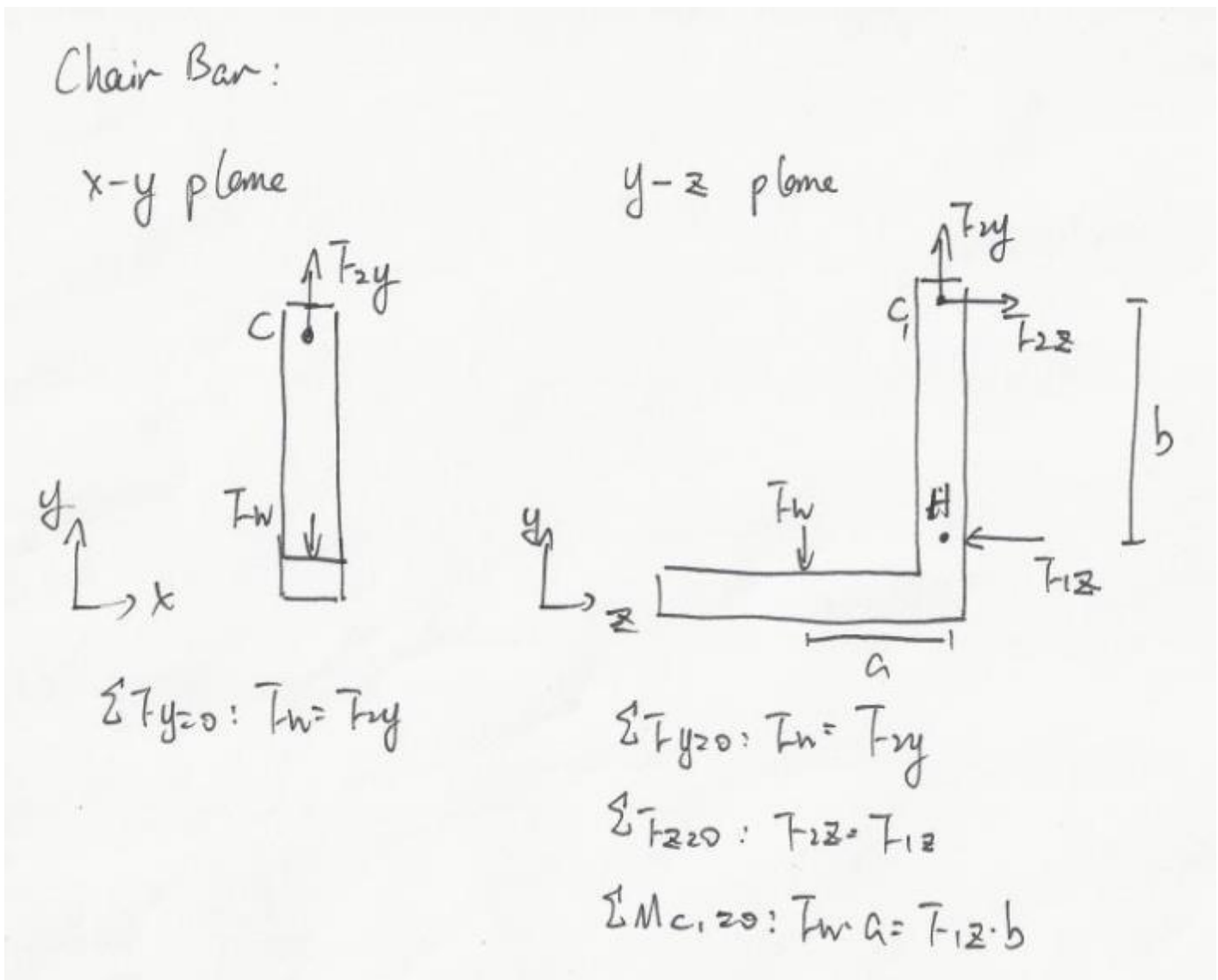


Figure 43: Free body diagram of the supporting bar for the chair.

The rod will also be put in tensions as a result of the Z direction forces in the Y-Z plane. The result of the forces in the Y and Z direction are found in appendix C in table 4 on page 99. This is the free body diagram under our previously stated assumption: **The rod at location C1 as seen in (Figure 43) has an ultimate strength that will support the user's weight and that the rod will not fail by compression (bearing stress) or tear out of the material.**

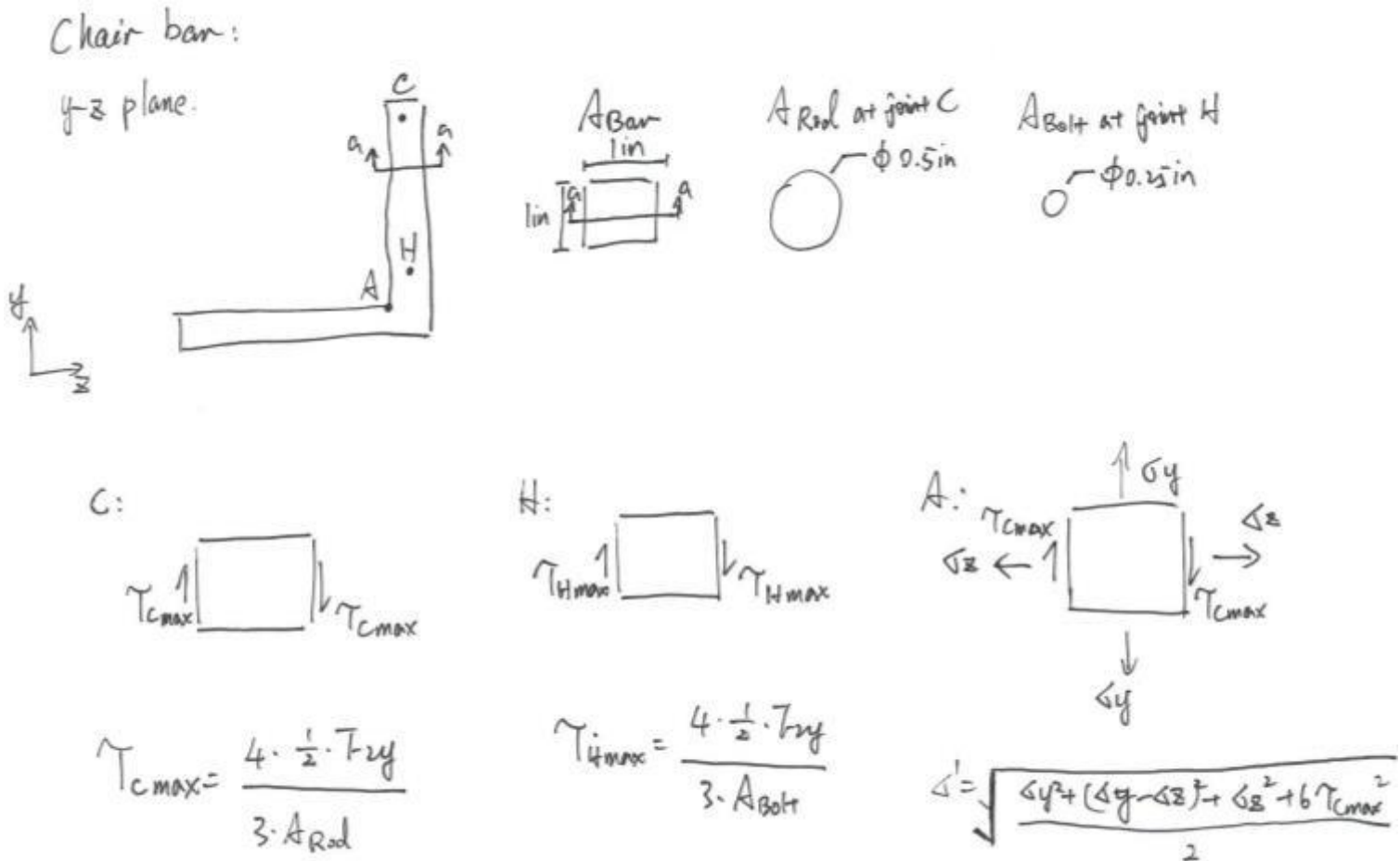


Figure 44: Stress on the chair bar and von mises stress equation. The shear stress equation is also in the figure.

The stress at point A in the figure 44 above is represented by the stress cube after A in the bottom left of the figure. The cube is in tension as a result of the user's weight. Point C represents the tear out stress of the chair. Point H represents the location where the angled bar is bolted to the chair in shear. The stress results are in appendix D in table 12 on page 105. The shear stress in cubes C, H, and A are taken at the max. In order for the shear stress to cause the material to fail by tear out there has to be failure on each side of the material. This is represented by $\frac{1}{2}$. Shear on the rods will be larger because of this factor and depending on the area of the section that is being sheared. The largest shear stress for the chair is occurring at point H (pin) where the angled bar attaches as seen in (figure 41).

Chair Rod at joint C:

y-z plane:

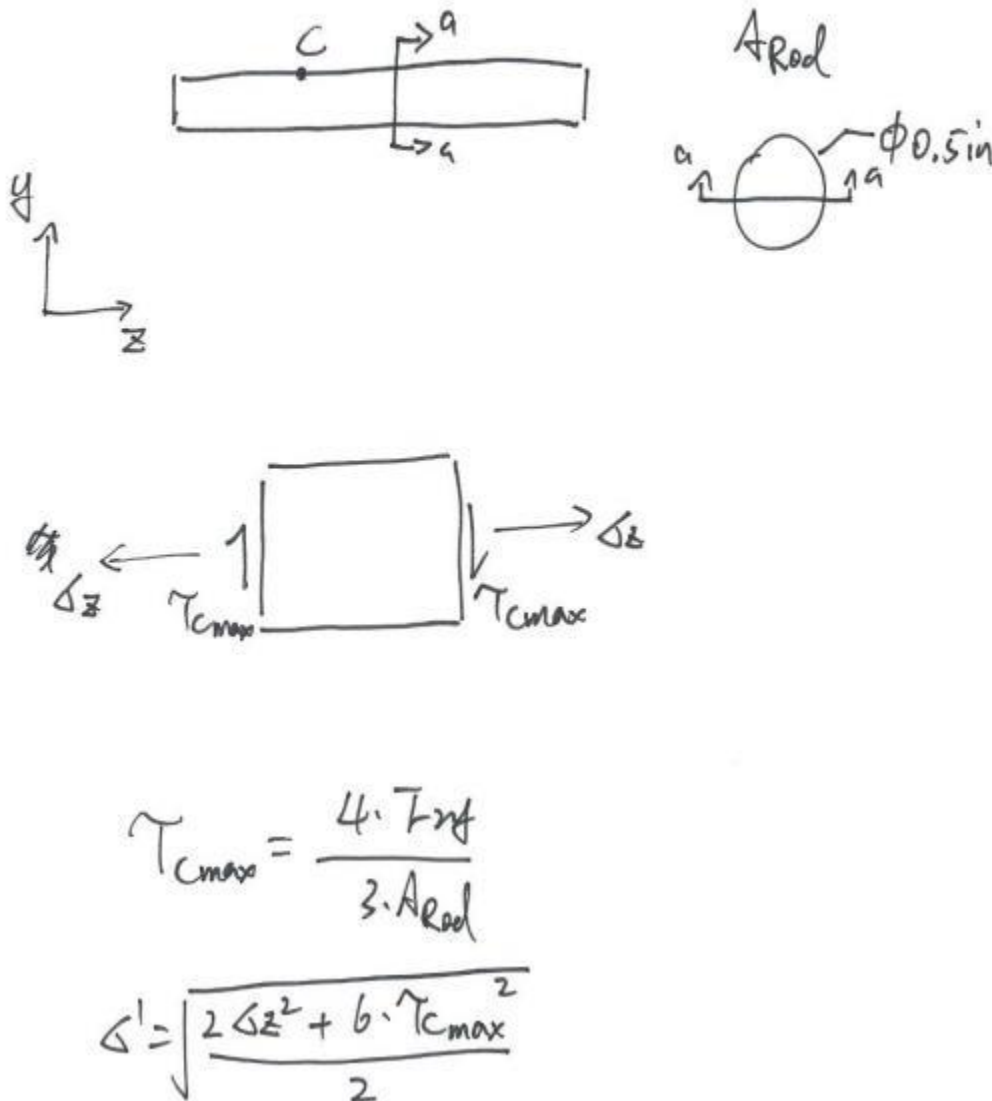
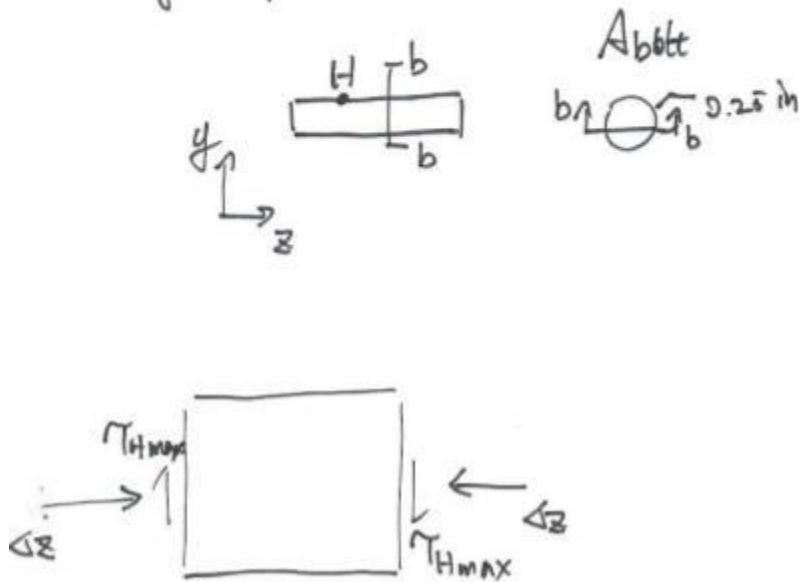


Figure 45: Stress on the chair rod and von mises stress equation. The shear stress equation is also in the figure.

The stress at point C in the figure 45 above is represented by the stress cubes C1 and C2 in the bottom left and right of the figure. The cube C1 is in tension as a result of the user's weight and the chair pulling on the rod in the z direction. It is also in direct shear with link 3(main link) represented by stress cube. The stress results are in appendix D in table 12 on page 105. Rod c will experience a shear stress much less than at point H as seen in the stress results in appendix D on page 105.

Chair Bolt at joint H:

y-z plane:



$$\tau_{Hmax} = \frac{4 \cdot T \cdot y}{3 \cdot A_{bolt}}$$

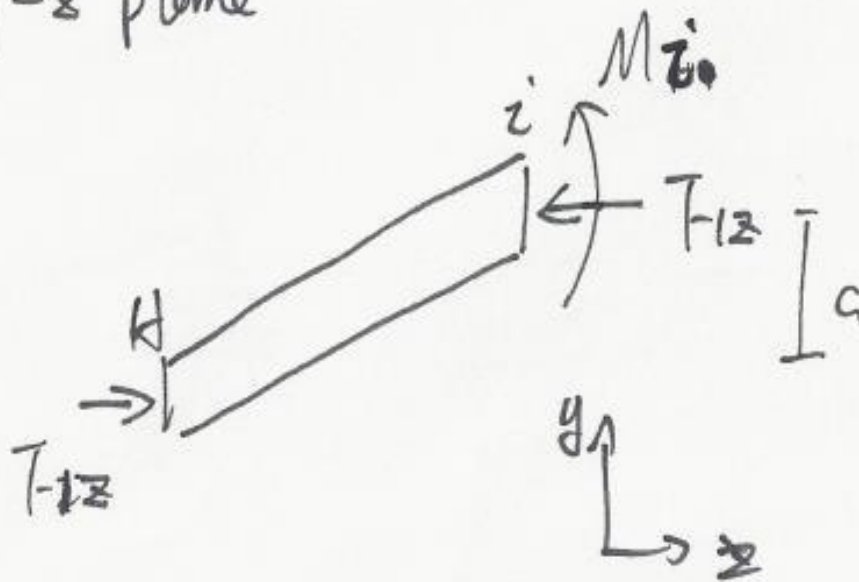
$$\sigma' = \sqrt{\frac{2 \cdot \sigma_z^2 + 6 \cdot \tau_{Hmax}^2}{2}}$$

Figure 46: Stress on the pin H where the angle bar connects to the chair and von mises stress equation. The shear stress equation is also in the figure.

The stress at point H in the figure 46 above is represented by the stress cubes after H1 and H2 in the bottom left and right of the figure. The cube H1 is in compression as a result of the user's weight and the Z direction force on the bottom of the chair. The pin is also in direct shear with the chair represented by stress cube H2. The stress results are in appendix D in table 12 on page 105. The pin at point H will have a shear stress of 6111.6 psi., which was taken into consideration when the material was chosen to maintain a safety factor of 3.

Chair back angle bar

y-z plane



$$\sum T_z = 0: T_{12} = T_{12}$$

$$\sum M_i = T_{12} \cdot Q$$

Figure 47: Free body diagram of the angled chair support.

The angled bar as seen in (figure 47) will only have Z direction forces. The Y direction force does not exist in the free body diagram because of the previous assumption. The Z direction force on the angled bar will create a moment at joint location (I) as seen in the free body diagram in (figure 47). The moment from the bar will be a result of the displacement in the y direction from the joint location and the Z direction force. The force results are in appendix C table 5 on page 99.

Chair Back Angle Bar and pin i.

y-z plane:

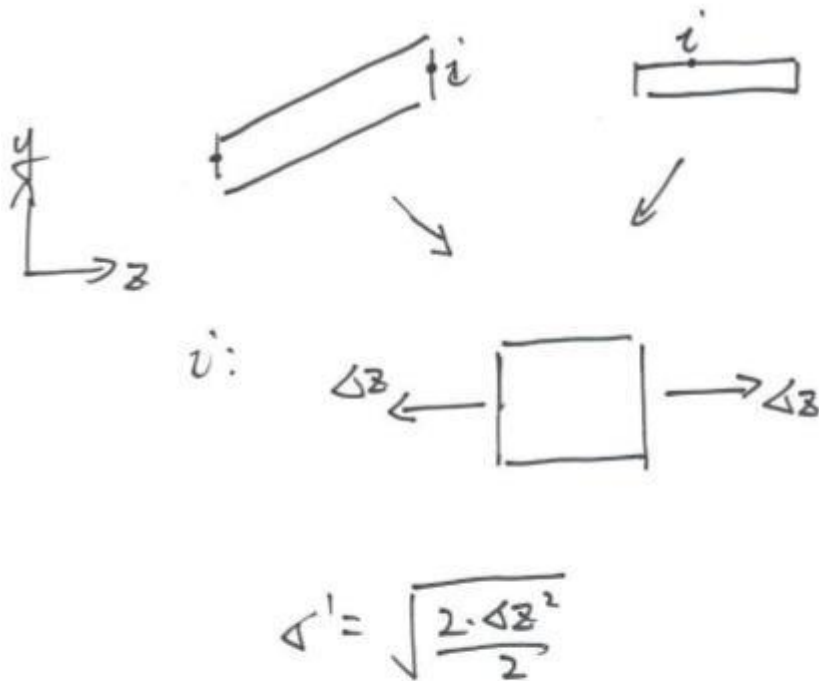


Figure 48: Stress on the angled bar connects to the chair and straight back support bar with von mises stress equation.

The stress at point H and I in the figure 48 above is represented by the stress cubes after H and I in the bottom left and right of the figure. The cube H is in tension as a result of the user's weight and the z direction force on the bottom of the chair. The pin is also in direct shear with the back support bar represented by stress cube I. The stress results are in appendix D in table 13 on page 105.

The chair back straight bar as seen in (Figure 49) on page 57 has a force analysis that results from the angled bar and the chair link. The results of the forces are in appendix C table 6. The straight back support is considered kinematic link 4 and connects kinematic links 2 and 3. The Free body diagram is drawn in equilibrium on page 57 in (Figure 49). The force results are in appendix B table 6 on page 99

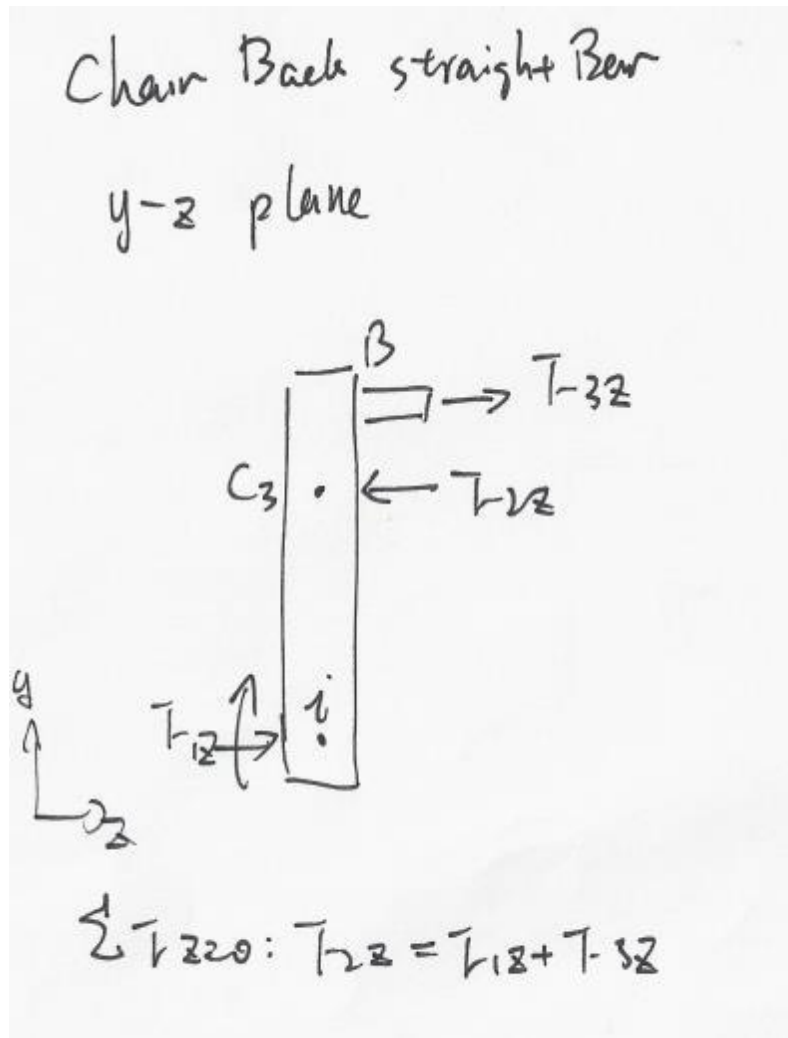


Figure 49: Free body diagram straight back bar support that connect the chair and the angled bar

The force at a joint location (B) as seen in figure on page results in a Z direction force of 0. The joint locations (C3 and I) will balance. The nut behind link 4 at location joint (C3) will prohibit the translation in the positive Z direction. The moment will prohibit the piece from rotating. This results in link 2 being a 0 force member. There is no X, Y, or Z direction forces. The function of link 2 is to prohibit the chair from swinging in the positive or negative x direction as seen in the X-Y plane when the user's center of gravity shifts from the center of the chair as seen in the free body diagram for the chair.

Chair Back Straight Bar:

y-z plane

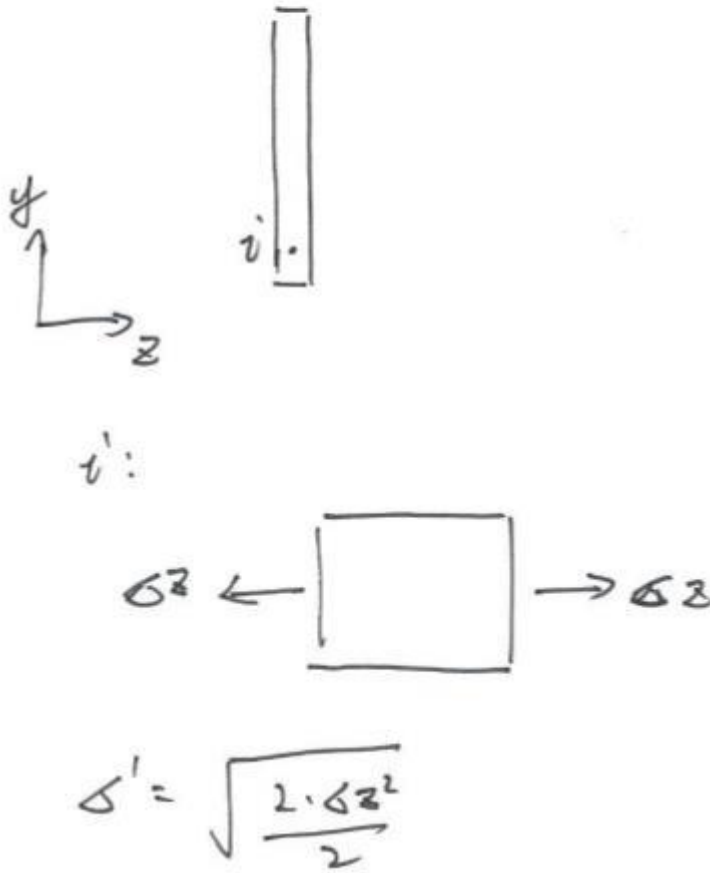


Figure 50: Stress on straight back support bar from the angled bar with von mises stress equation.

Figure 50 shows the stress cube for the straight back support bar at location (joint I). The bar is in tension as indicated by the z direction stress as a result of the angled bar. The von mises stress will be equivalent to the z direction stress.

Link 3 (parallel links) will only have Y direction forces at joint locations C1. The whole link will not have any Z direction forces. Joint locations E1, E2, D1, and D2 will have X and Y forces as seen in the free body diagram in (figure 51) on page 59. The left side of link 3 in the Z-Y plane shows compressive forces from the chair and base links at joint locations (C1 and D1) on page 60 in (figure 52). The actuator will exert X and Y direction forces on link 3 at locations (E1 and E2). Joint location (D2) will pull on the base link due to the force from the user. The results will change over time. The results are in appendix C in table 7 on page 100.

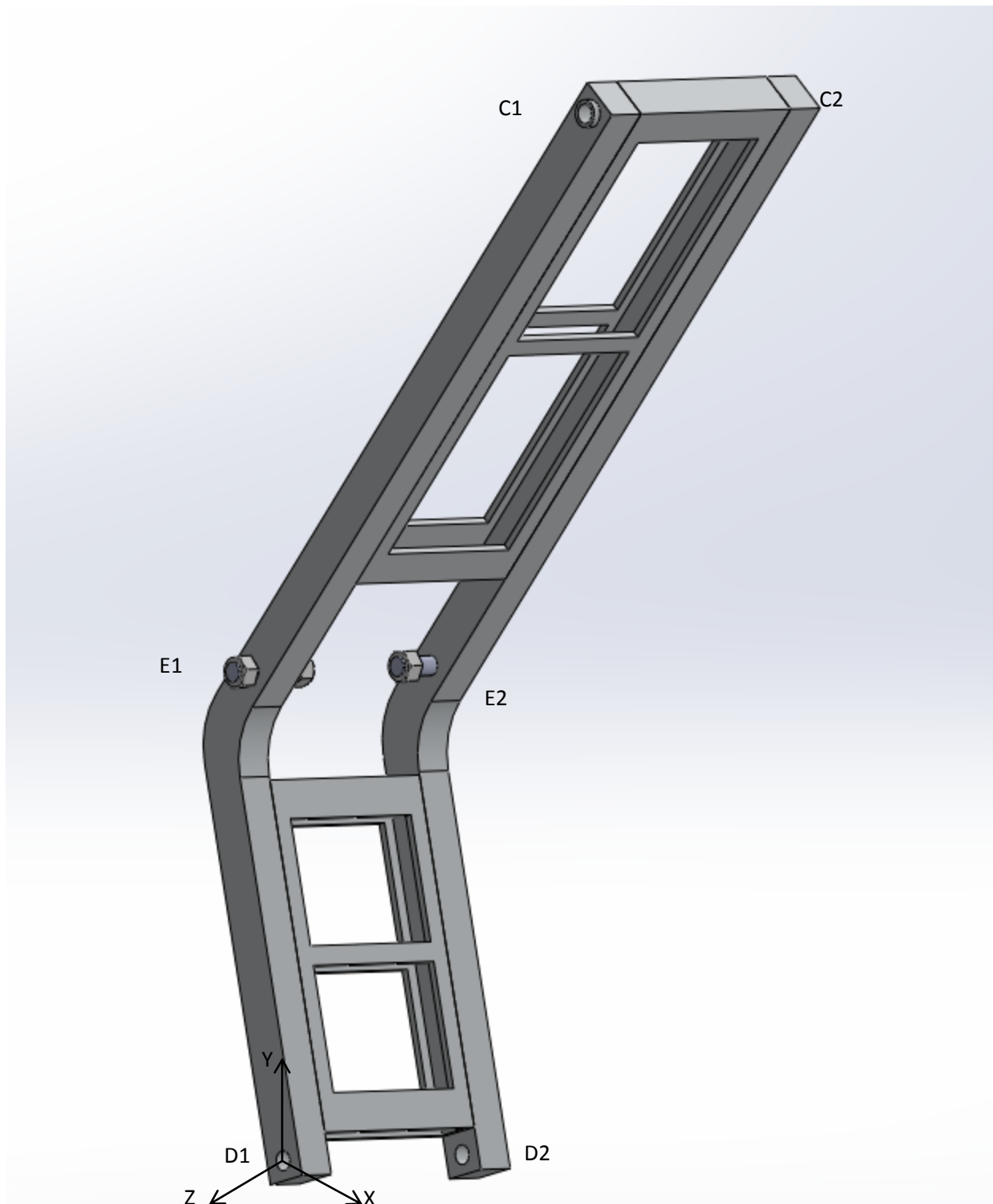
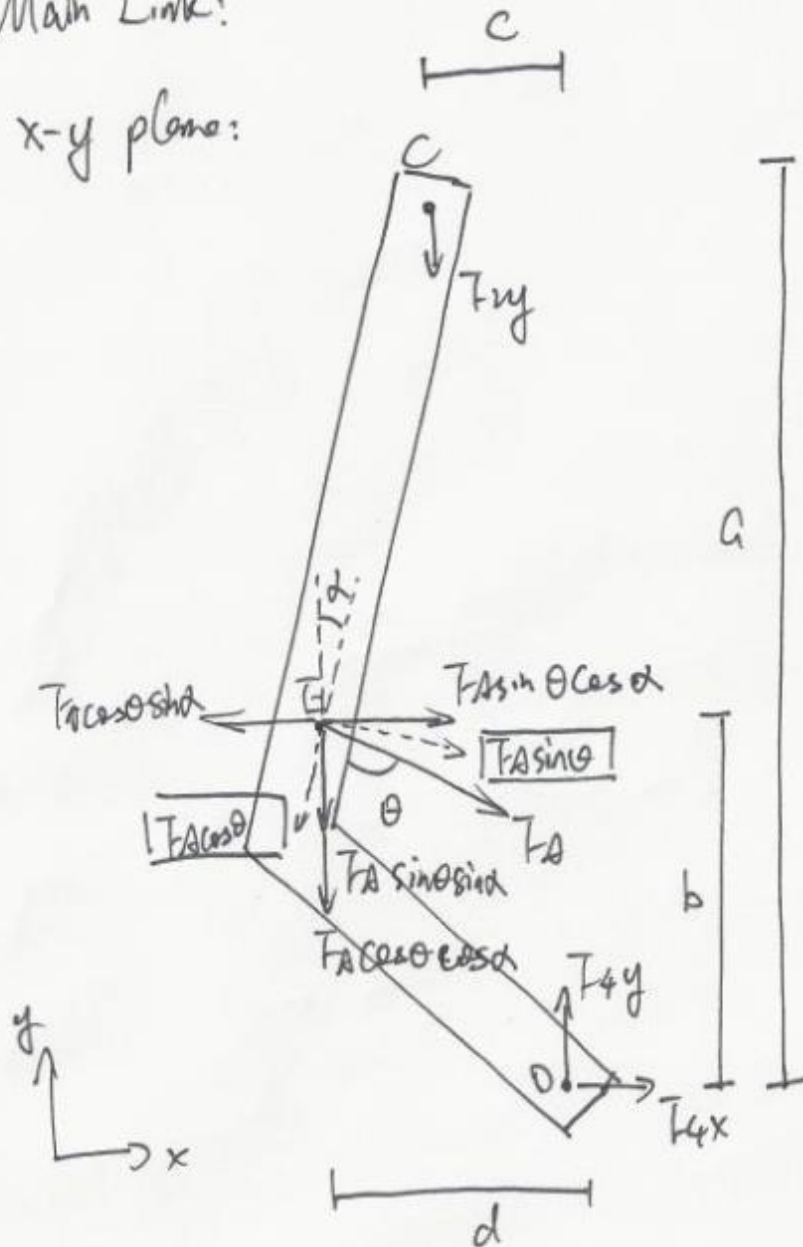


Figure 51: Assembled isometric view of link 3

Main Link:

x-y plane:



$$\sum F_x = 0: T \cos \theta \sin \alpha + T_{4x} - T \sin \theta \cos \alpha = 0$$

$$\sum F_y = 0: T_{xy} + T \sin \theta \sin \alpha + T \cos \theta \cos \alpha - T_{4y} = 0$$

$$\sum M_O = 0: T_{xy}c + T \cos \theta \sin \alpha \cdot b + T \sin \theta \sin \alpha \cdot d + T \cos \theta \cos \alpha \cdot d - T \sin \theta \cos \alpha \cdot b = 0$$

Figure 52: Free body diagram (X-Y) plane view of the link 3 (main link)

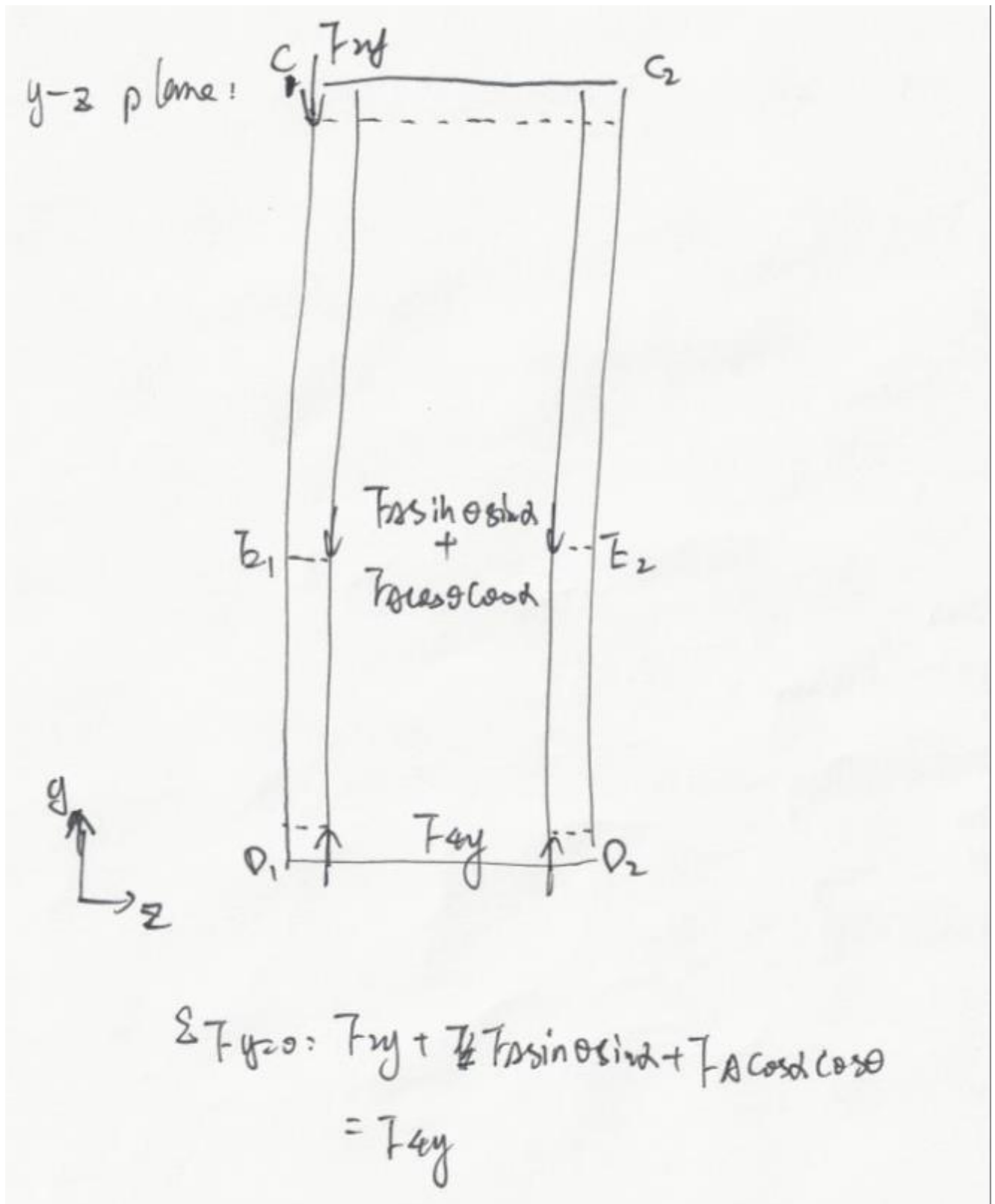


Figure 53: Free body diagram (Z-Y) plane view of the link 3 (main link)

Main Link:
x-y plane:

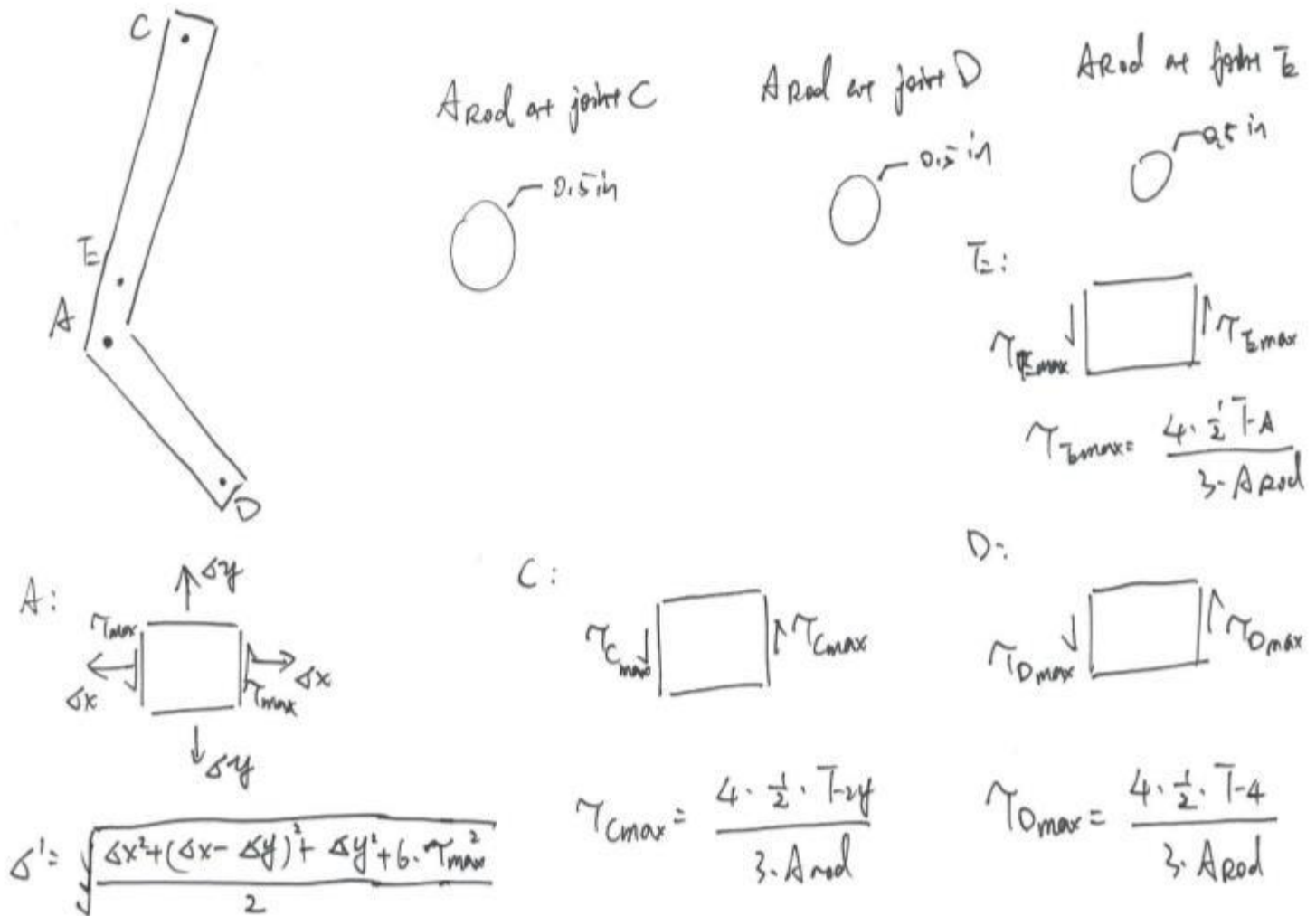


Figure 54: Stress on the kinematic link 3 von mises stress equation.

Figure 54 shows the stress cube at location A in tension from the actuator forces and chair causing the link to bend. The results are in table 15 on page 105. The actuator forces and stress will be discussed on page 67. The other stress cubes represent the shearing stress from the chair at C, the actuator at E, and the pin joints at D. point E on the figure above will experience the highest shear stress from the actuator pin joint. The shear stress is 4617.5 psi., which was taken into consideration when the material was chosen to maintain a safety factor of 3.

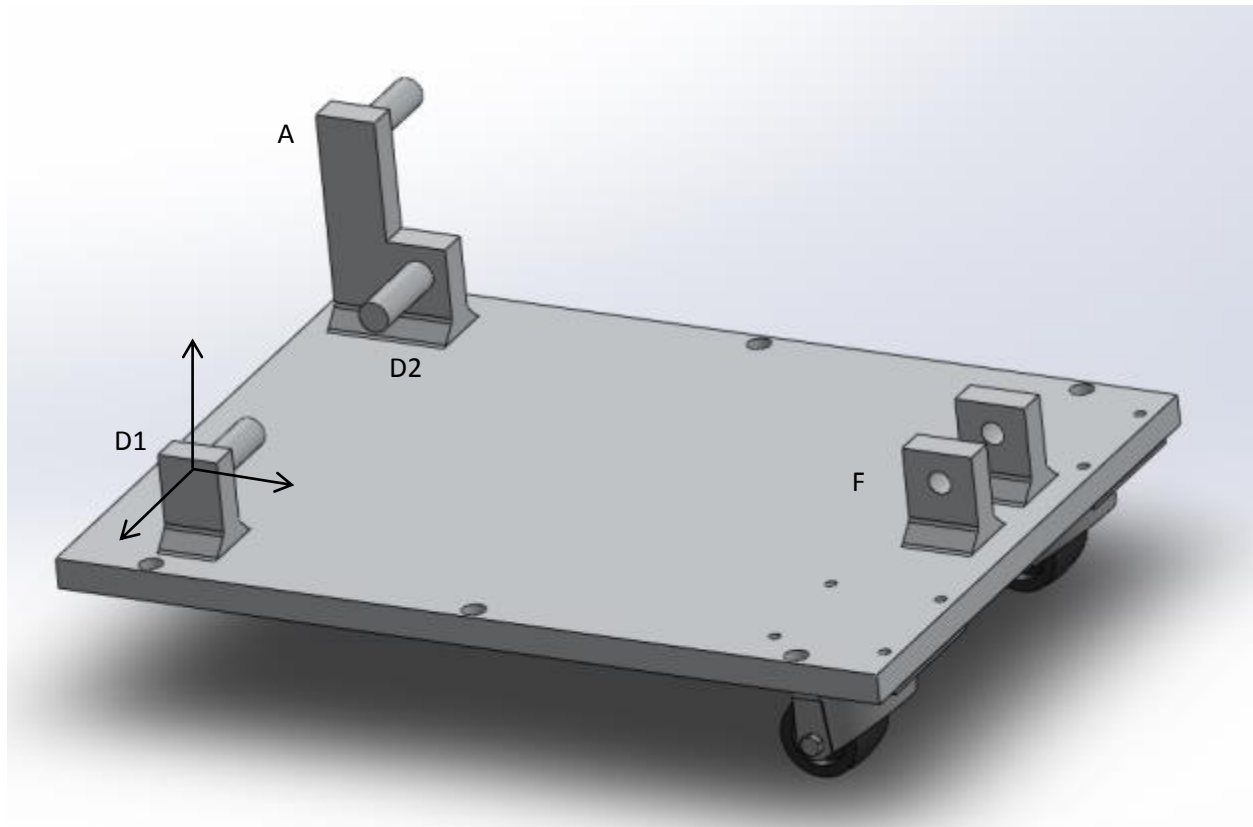
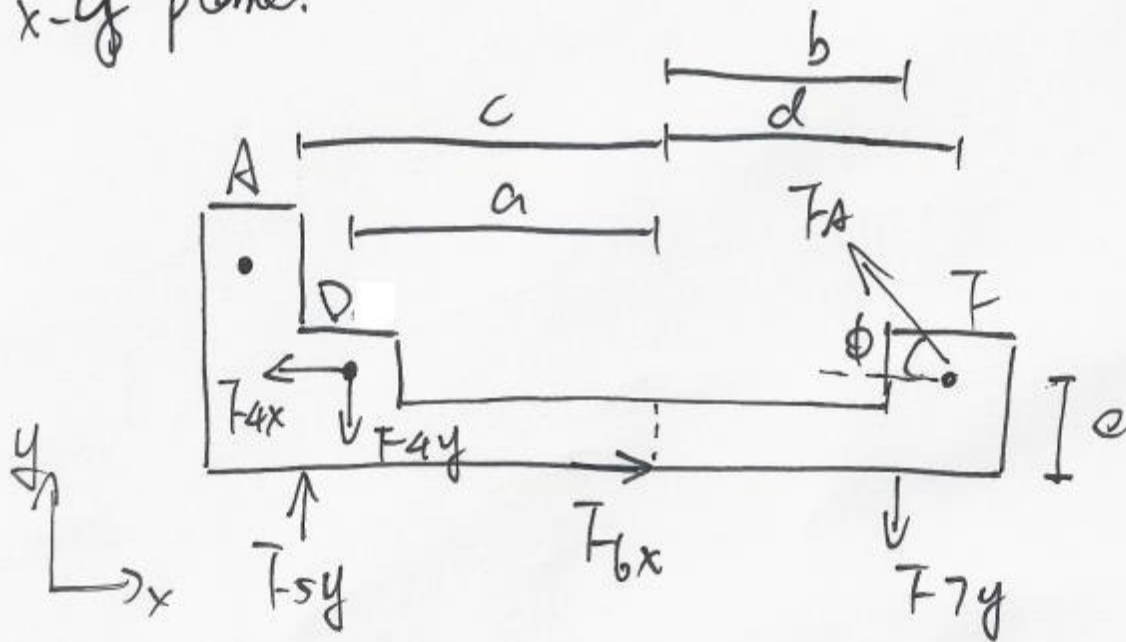


Figure 55: isometric view of the base link

The base link will have resulting forces from link 3 and links 5 and 6 (The actuator). The free body diagram for the base is seen in (figure 56). The results of the base link forces are in table 8 on page 101.

Base Link.:

x-y plane.



$$\sum F_{x20}: F_{4x} + F_A \cos \phi = F_{6x}$$

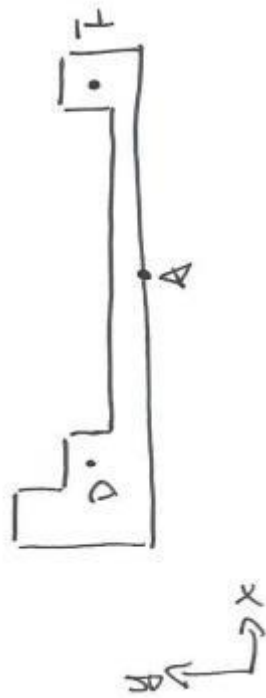
$$\sum F_{y20}: F_{4y} + F_{7y} = F_{5y} + F_A \sin \phi$$

$$\sum M_{F_6} = 0: F_{4x} \cdot e + F_{4y} \cdot a - F_{5y} \cdot c - F_{7y} \cdot b + F_A \cos \phi \cdot e + F_A \sin \phi \cdot d = 0.$$

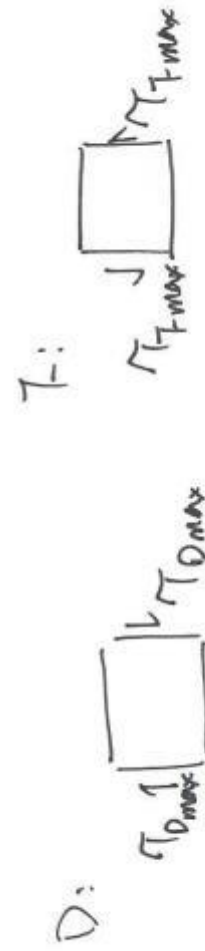
Figure 56: Free body diagram of kinematic link 1 in the X-Y plane

Base Link:

x-y plane.



A rod at joint F
 $\sim 0.38 \text{ in}$
 $\sim 0.25 \text{ in}$
 $A_{\text{bolt at joint A}}$



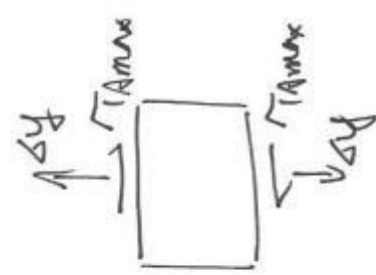
$$\tau_{Dmax} = \frac{4 \cdot \frac{1}{2} \cdot T \cdot 4}{3 \cdot A_{rod}}$$

$$\tau_{Dmax}' = \frac{4 \cdot T \cdot 4}{3 \cdot A_{rod}}$$

$$\tau_{Tmax} = \frac{4 \cdot \frac{1}{2} \cdot T \cdot A}{3 \cdot A_{rod}}$$

$$\tau_{Tmax}' = \frac{4 \cdot T \cdot A}{3 \cdot A_{rod}}$$

A:



$$\tau_{Amax} = 4 \cdot \frac{1}{2} \cdot T \cdot 6x$$

$$\tau_{Amax}' = \frac{4 \cdot T \cdot 6x}{3 \cdot A_{bolt}}$$

$$\sigma' = \sqrt{\frac{2 \cdot \Delta y^2 + 6 \cdot \tau_{Amax}^2}{2}}$$

Figure 57: Stress on the base link 1 and the von mises stress equation. The shear stress equation is also in the figure.

The base link is shown with stresses at 6 locations. D1 and D2 are collinear pin joints in shear while A is the bolt underneath the base in tension and shear depend on the position of the chair. Point F stress also depends on position. The magnitudes of the forces are in table 17. the base link will experience the largest von mises stress as seen in table 17.

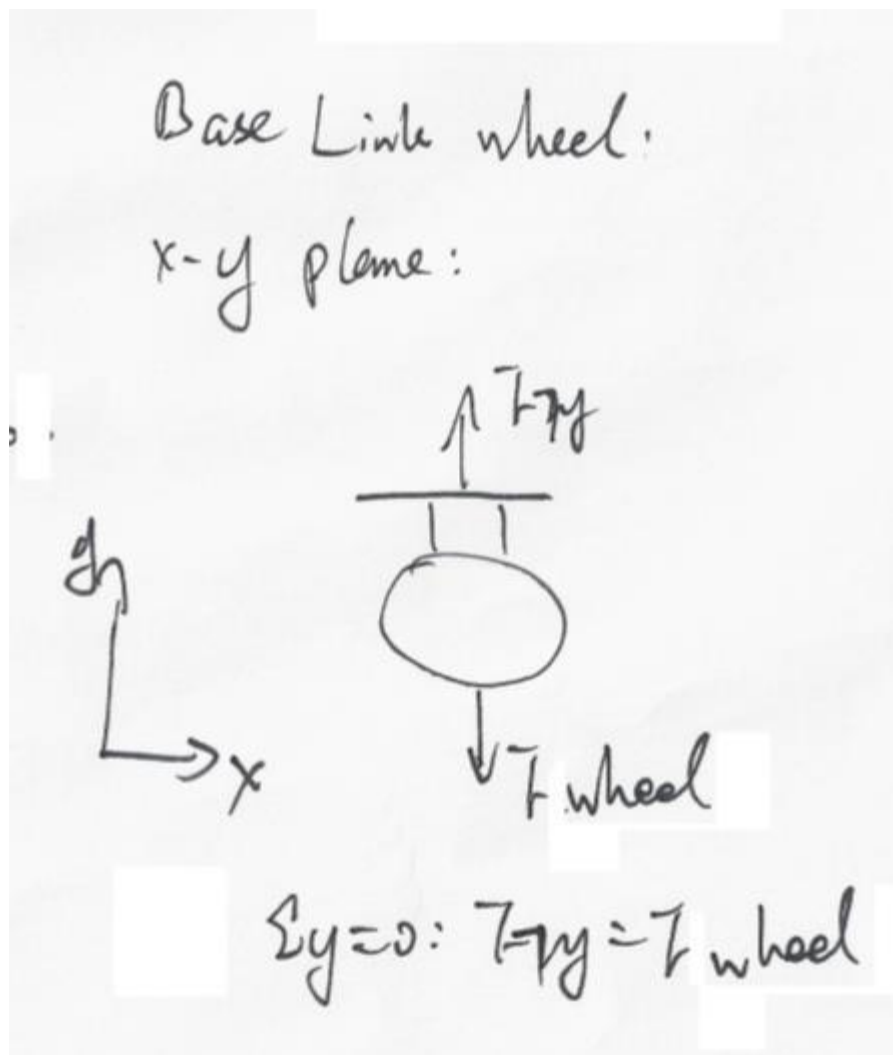
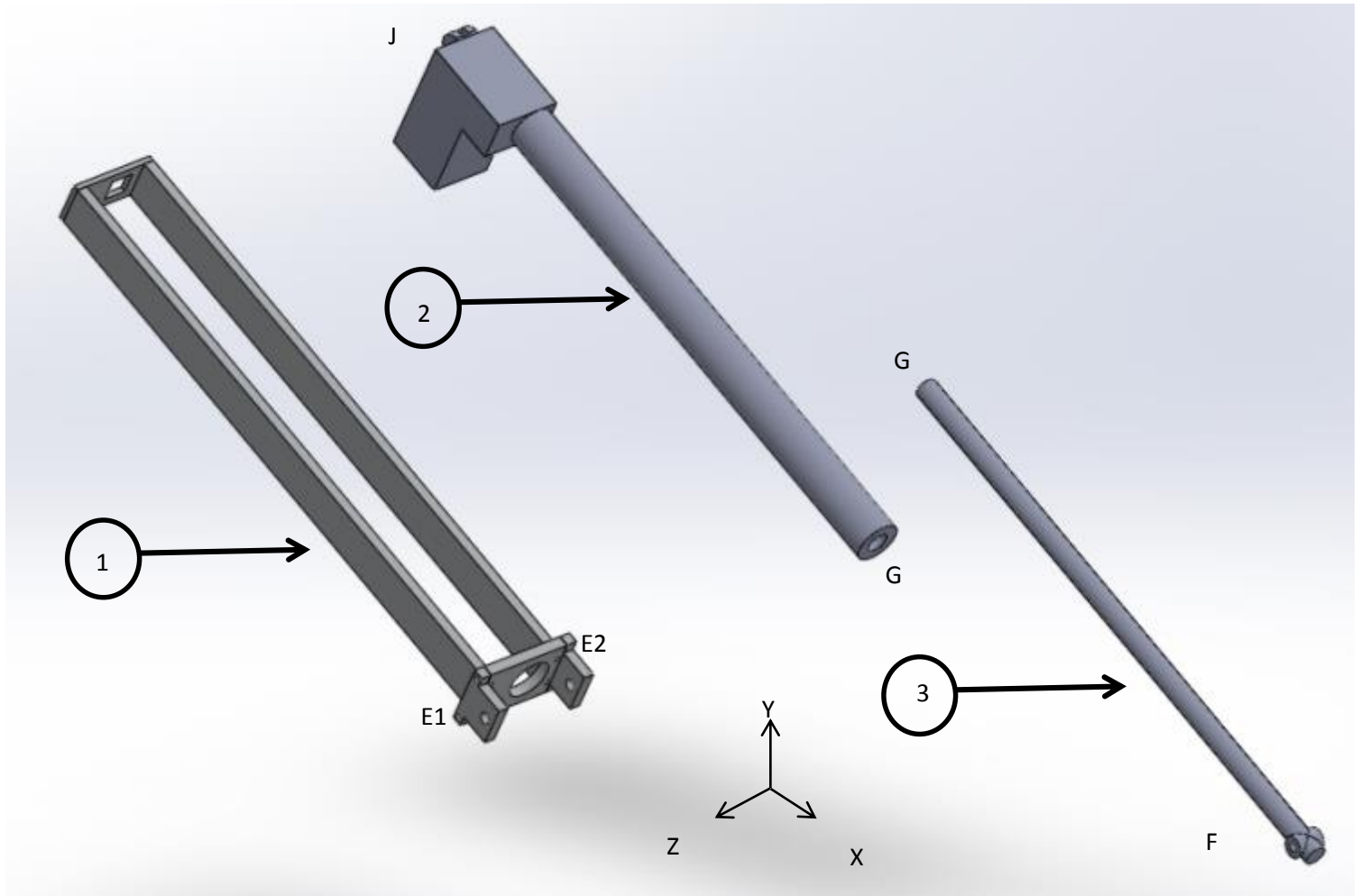


Figure 58: Free body diagram of the front wheels in the X-Y plane

Figure 58 shows the wheel of the front link base free body diagram.



1	Actuator holder
2	Actuator cylinder
3	Actuator piston

Figure 59: Exploded view of the actuator and holder

The actuator forces were calculated as a result of the position analysis and force analysis of link 3. The forces that the linear actuator will need to raise and lower the user in and out of the water will change over each position as cited earlier from the kinematic analysis. The free body diagram for the actuator cylinder and piston are seen on page 60 in (figure 60). The results of the forces for the free body diagram in figure 60 are in table 9 in appendix C on page 100.

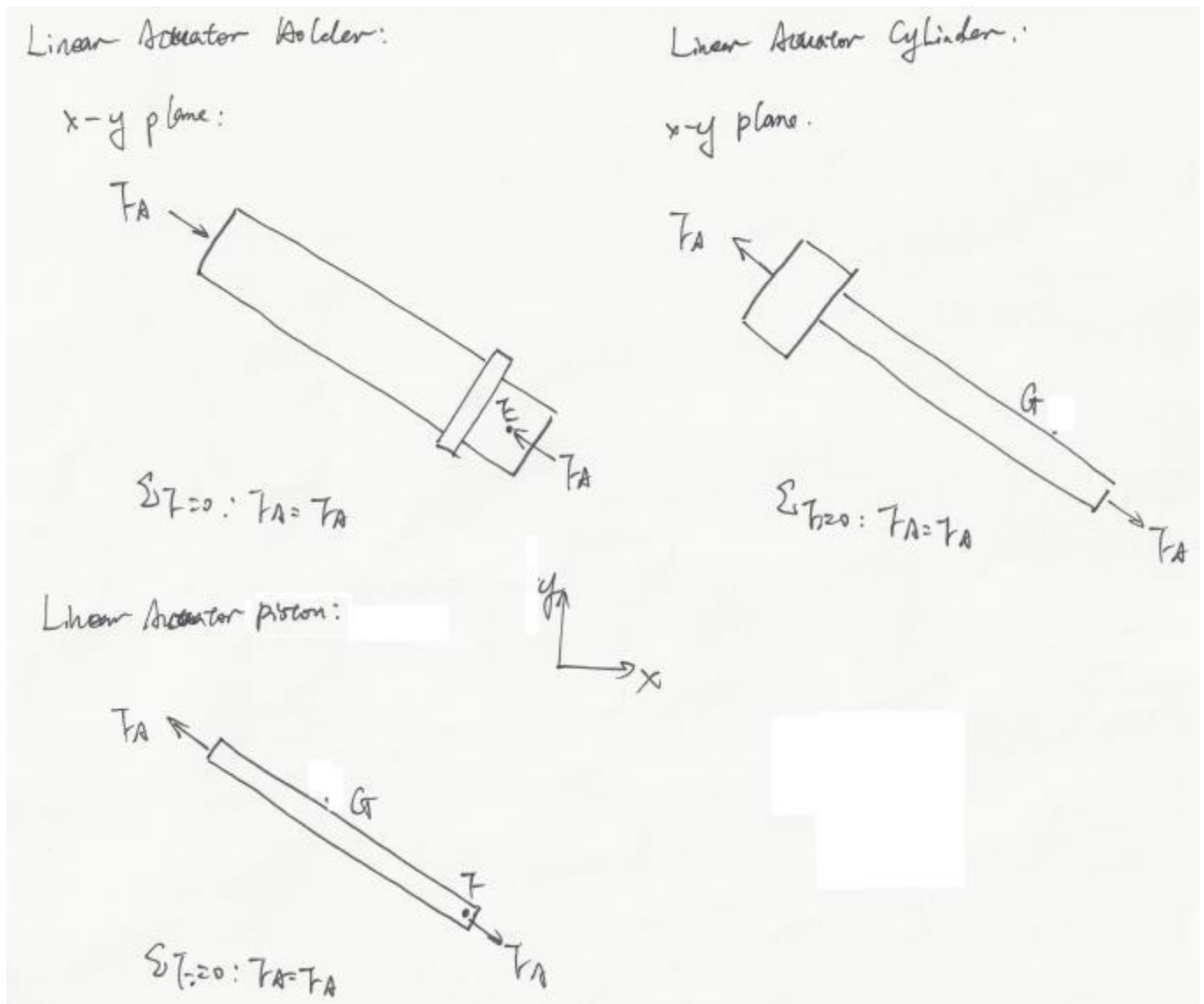


Figure 60: Actuator Assembly Free body diagrams in the X-Y plane.

Figure 60 indicates the magnitude of the forces on each of the components of the actuator assembly. The forces on the actuator are directly related to the position and force analysis of link 3 over 20 positions. The position of joints E1 and E2 will change over each position changing the forces to keep link 3 in equilibrium with the applied load of the user. The force analysis of link 3 at position 20, as seen in the appendix C results in table 7, show that there is a significant increase in force required to support the chair. The last position is indicated in red. The last position will increase the magnitude of force along the actuator by approximately 400 lbs. The design will be altered so that link 3 never reaches that position. This alteration will keep the forces low on the actuator and would decrease the cost of the actuator needed to lift and lower the chair in and out of the water. Removing this position will result in the stroke length of the actuator. The results of the forces on the actuator are in appendix C in table 7.

Linear Actuator Holder

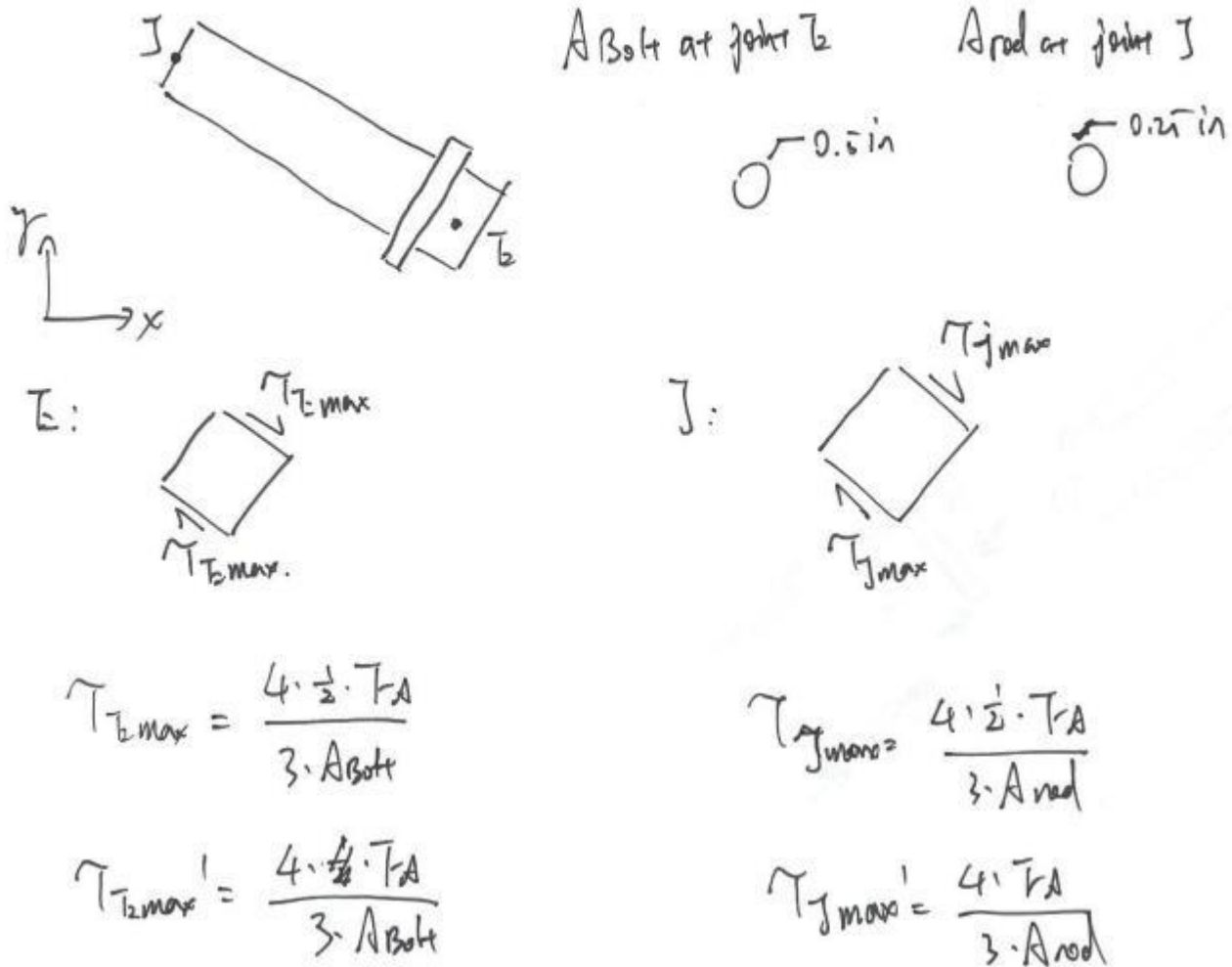
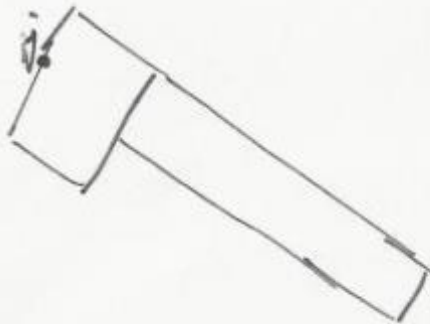


Figure 61: Stress on the Actuator holder and the von mises stress equation. The shear stress equation is also in the figure.

Figure 61 (actuator holder) shows the stress cubes for points A and E. Point A is in compression while Points E1 and E2 are both in shear with link 3 (main link). The stress results are in table 16 in appendix D.

Linear Actuator Cylinder



J:



$$\tau_j = \frac{F_A}{A_{ph\tau_j}}$$

Linear Actuator piston:



F:



$$\tau_F = \frac{F_A}{A_{ph\tau_F}}$$

Figure 62: Stress on the Actuator kinematic links 5 and 6 and the von mises stress equation. The shear stress equation is also in the figure.

Figure 43 (actuator cylinder and piston) shows the stress cubes for points J and F. Point J is in shear while Point F are both in shear with link 1 (base link). The stress results are in table 16.

The base link will exert forces on the square rods that connect the base to the counterweights that keep the entire device from overturning.

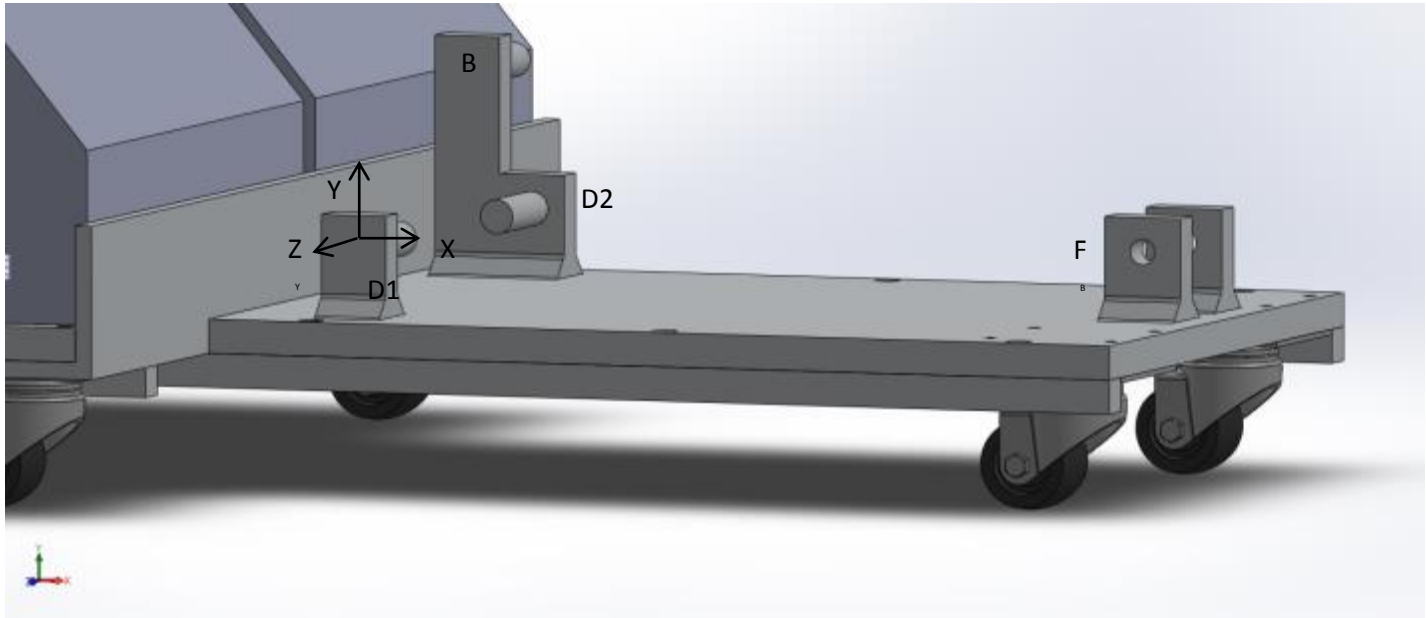


Figure 63: link 1 base in an isometric view to show the supporting bar underneath the base link

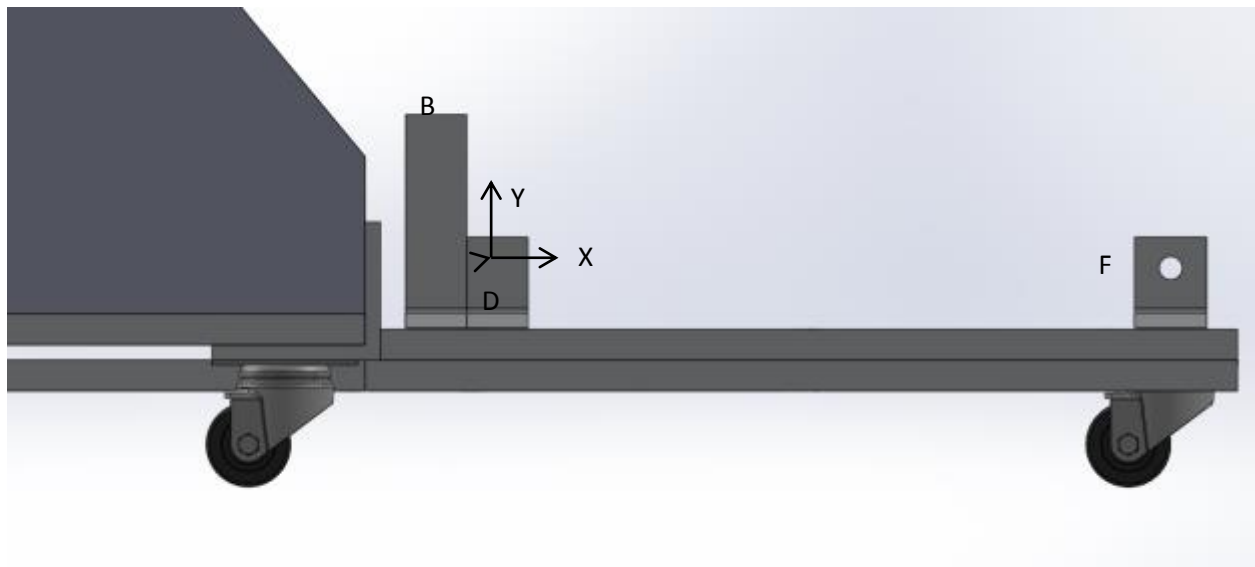
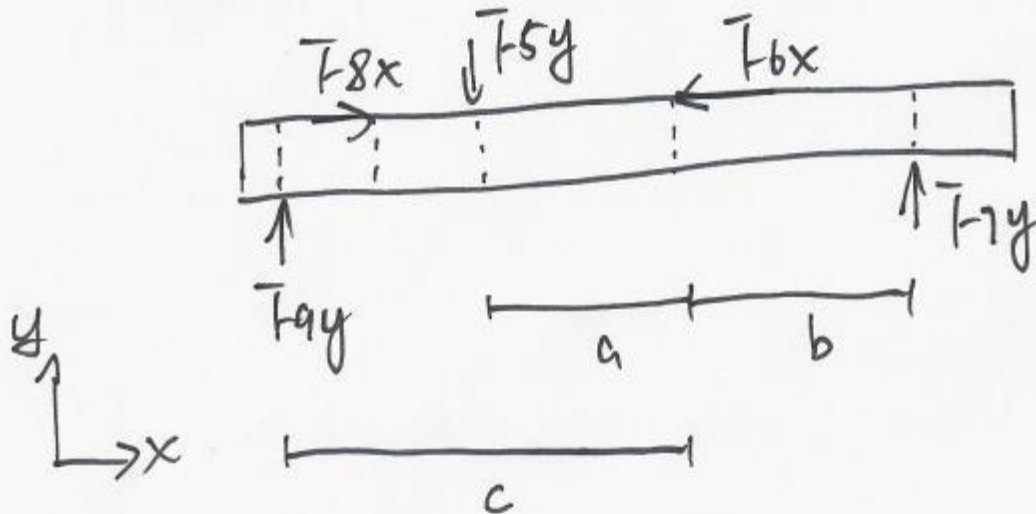


Figure 64: x-y plane view of the tank and the wheel

Base Bar!

x-y plane:



$$\sum T_x = 0: T_{8x} = T_{6x}$$

$$\sum T_y = 0: T_{9y} + T_{7y} = T_{5y}$$

$$\sum M_{T_6} = 0: T_{9y} \cdot c = T_{5y} \cdot a + T_{7y} \cdot b$$

Figure 65: Free body diagram of the square supporting rods in the X-Y plane

The following free body diagram shows the forces on the L shaped bracket and the counterweight wheels. The results of the forces on the base bar are in table 10 in appendix C on page 103.

Base Bar:

x-y plane

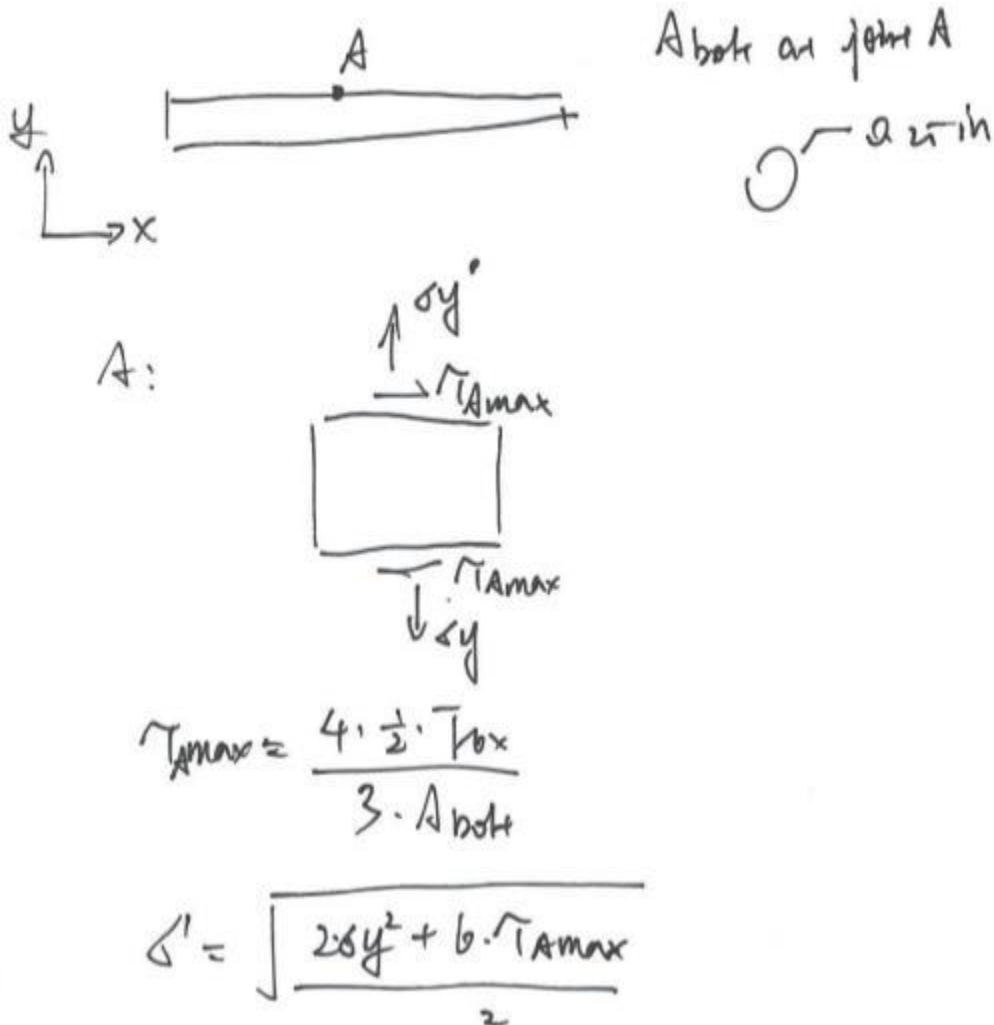
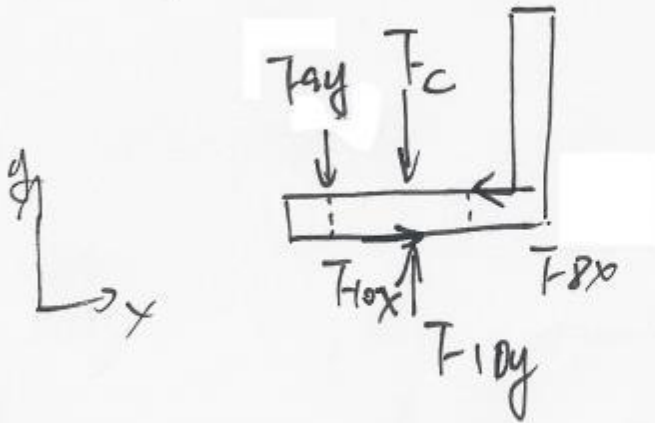


Figure 66: Stress on the base bar under link 1 and the von mises stress equation. The shear stress equation is also in the figure.

Figure 66 shows the stresses on the base bar under base 1. Point A is collinear. A1 represents bar in compression while A2 and A3 represent the shearing of the bolt. The results of the stresses are in table 18 in appendix D.

Tank Bar:

x-y plane:



$$\sum T_{y20}: T_{ay} + T_c = T_{10y}$$

$$\sum T_{x20}: T_{10x} = T_{8x}$$

Tank Wheel:

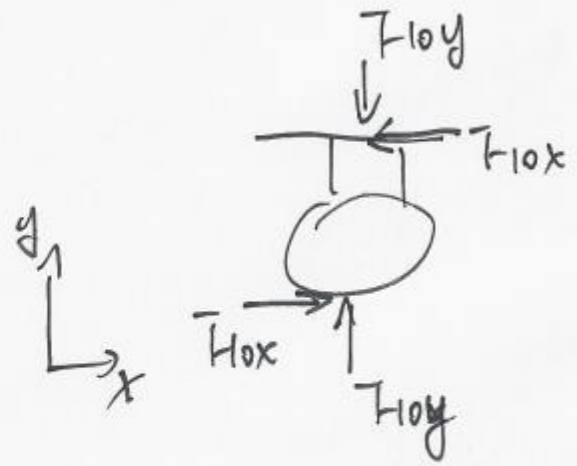
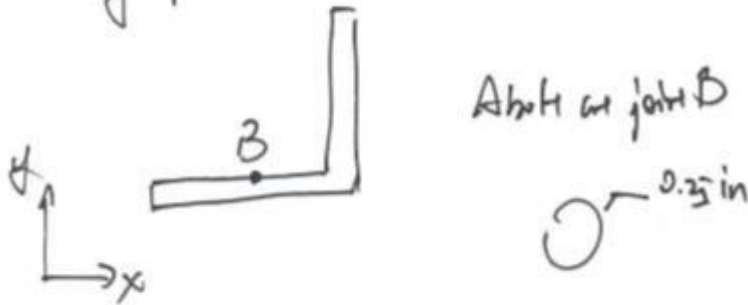


Figure 67: Free body diagrams for the I shaped bar supporting the counterweight tanks and wheel free body diagram in the X-Y plane.

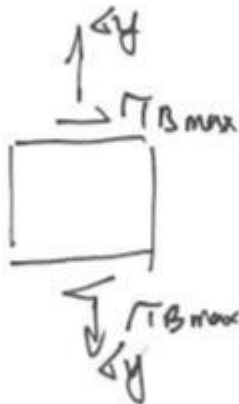
The tank bar and wheel support the counterweight and attach to the device. The results of the forces on the tank bar are in table 11 in appendix C on page 104.

Tank Base:

x-y plane:



B:



$$\tau_{Bmax} = \frac{4 \cdot \frac{1}{2} \cdot T_{8x0}}{3 \cdot A_{bolt}}$$

$$\tau_{Bmax}' = \frac{4 \cdot T_{8x}}{3 \cdot A_{bolt}}$$

$$\sigma' = \sqrt{\frac{2 \cdot \Delta y^2 + 6 \tau_{Bmax}}{2}}$$

Figure 68: stresses on the tank base with the von mises equation and shear stress equations.

The tank base stress are represented above I figure 68. Point A is collinear and will be in compression from the counterweight and base link 1. It is also in shear due to the force shearing the bolt to keep it together. The results of the stresses are in table 19 in appendix D.

The second case assumption is: **the load from the user is shared between the fixed bar and the upper rod.** The result would be a transfer of forces through the angled bar to the straight back support piece back to the rod.

Results

Final result

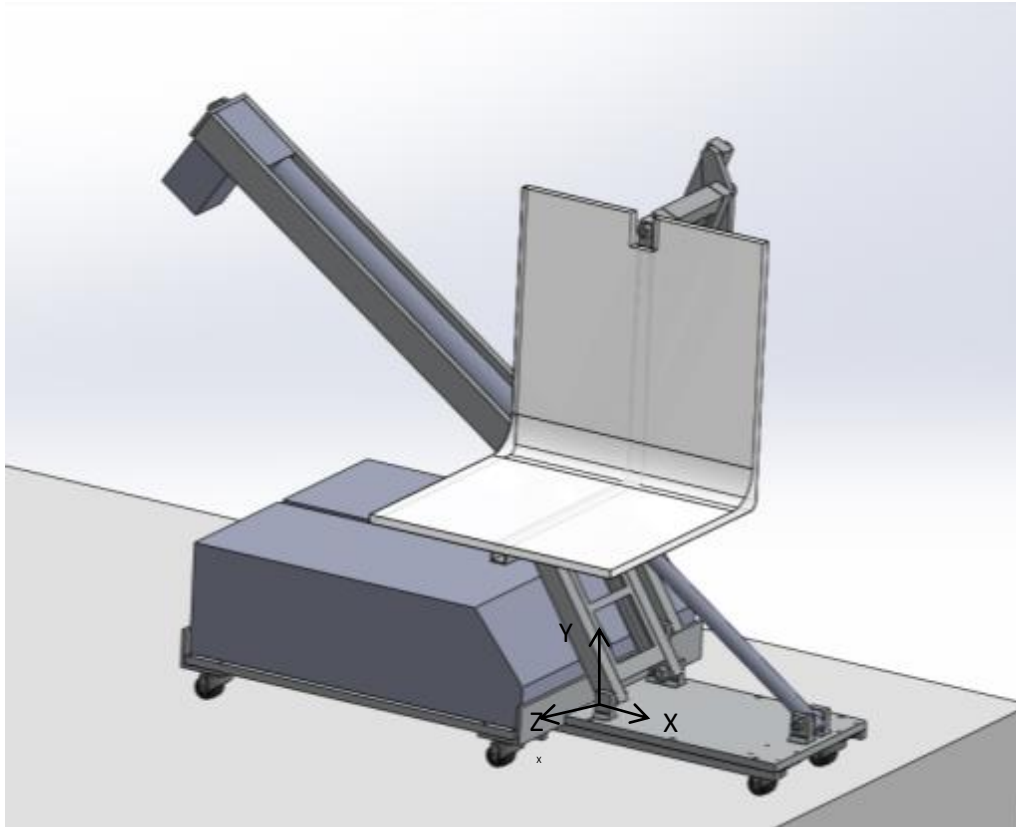


Figure 69: The image above shows the Final result after the design had been iterated numbers times.

The device is now reflective of the materials list below. The bar and rods are represented by the joints and kinematic links in the previous figures.

Chair Bar	Corrosion-Resistant High-Strength Aluminum (Alloy 7075)	Yield Strength of 56,000 psi
Chair Rod C	Alloy 20 stainless steel	Tensile strength of 80,000psi
Chair Bolt H	Black-Oxide 18-8 Stainless Steel	Tensile strength of 70,000 psi
Chair Back Angle Bar	Multipurpose Aluminum (Alloy 6061)	Yield Strength of 35,000 psi
Chair Back Bar Bolt I	Black-Oxide 18-8 Stainless Steel	Tensile strength of 70,000 psi

Chair Back Straight Bar	Multipurpose Aluminum (Alloy 6061)	Yield Strength of 35,000 psi
Main Link	Corrosion-Resistant High-Strength Aluminum (Alloy 7075)	Yield Strength of 56,000 psi
Main Link Pin E	Black-Oxide 18-8 Stainless Steel	Tensile strength of 70,000 psi
Main Link Pin D	Black-Oxide 18-8 Stainless Steel	Tensile strength of 70,000 psi
Actuator Holder	Multipurpose Aluminum (Alloy 6061)	Yield Strength of 35,000 psi
Actuator Holder Rod J	Alloy 20 stainless steel	Tensile strength of 80,000psi
Actuator Holder Pin E	Black-Oxide 18-8 Stainless Steel	Tensile strength of 70,000 psi
Base Link	Corrosion-Resistant High-Strength Aluminum (Alloy 7075)	Yield Strength of 56,000 psi
Base Link Bolt F	Black-Oxide 18-8 Stainless Steel	Tensile strength of 70,000 psi
Base Bar	Multipurpose Aluminum (Alloy 6061)	Yield Strength of 35,000 psi
Base Bolt 6x	Black-Oxide 18-8 Stainless Steel	Tensile strength of 70,000 psi
Tank Bar	Multipurpose Aluminum (Alloy 6061)	Yield Strength of 35,000 psi
Tank Bolt 8x	Black-Oxide 18-8 Stainless Steel	Tensile strength of 70,000 psi

Figure70: Materials list for each part

Half-Size Physical Model

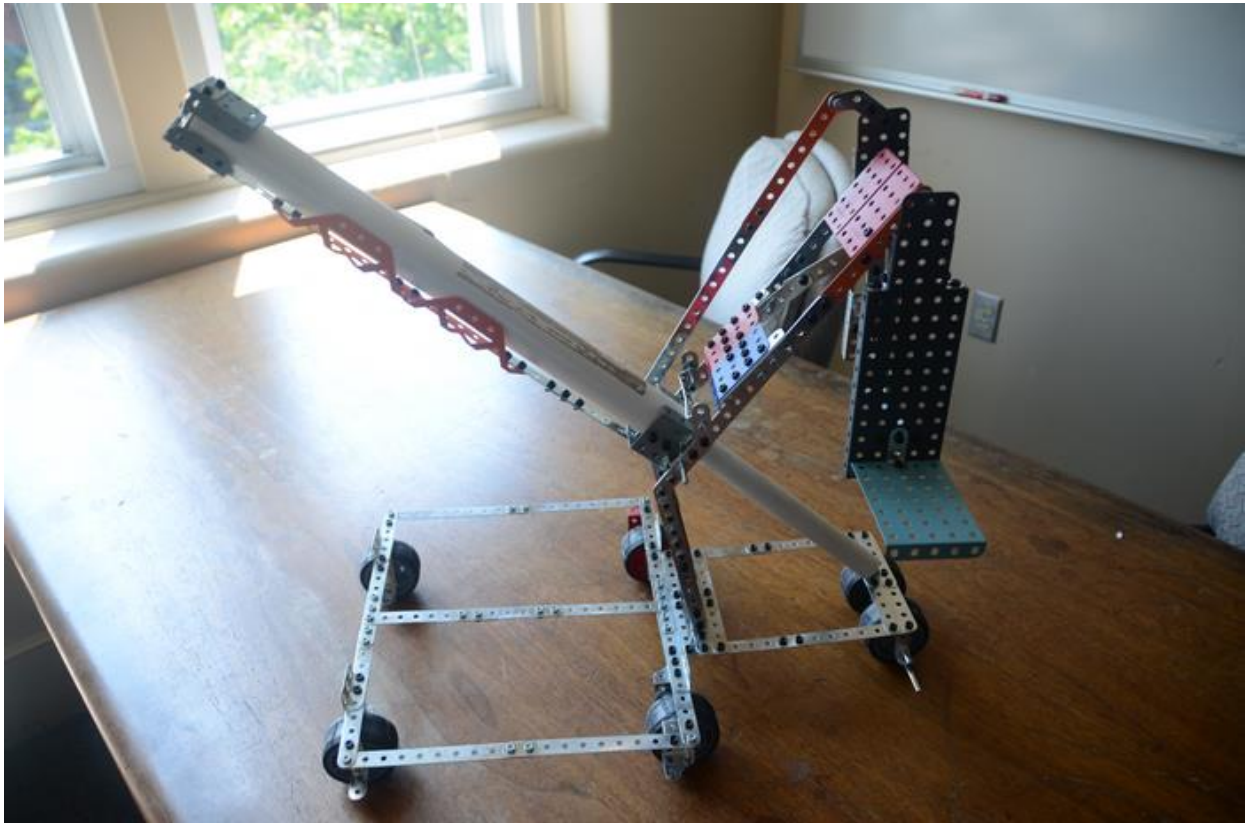


Figure 71: The half-size physical model of the pool lift device.

Figure 71 shows an approximate half-size physical model of the device the team constructed using pieces from several erector sets. The model was created from half sized dimensions of the model created in solid works. The model was able to achieve a depth proportional to the full size model of approximately 9 inches. The ADA indicates a depth of 18 inches below to the water line in the pool to be ADA compliant. The only items missing from the model are the counterweight tanks to keep the device from overturning. For the demonstration books were used to keep the model from overturning. In order to demonstrate the electronic linear actuator used in the full size design PVC piping was used in combination with erector set pieces. When testing the physical model, the base and the actuator were things that stood out. The actuator could potentially rotate when fully retracted. The actuator on this model may have rotated due to the design and the fact that the physical model does not have an actual linear actuator. The base would appear to need more support where the base bars connect the base link to the counterweight base. The links at that location where the bars connect to the counter weight would bulge implying high stress and forces. The wheels in the center would have a tendency to lift off of the ground if the counterweight was not sufficient. This could be due to the cross sectional area of the erector set links as well.

Conclusion

The goal of this project was to create a device that lifts and lowers a human safely in and out the pool. The outcome of this project created a working design of a device that achieves the desired kinematics and positions for the chair as set forth by the ADA. The design was created using 3 position syntheses from the design of machinery book from Professor Robert Norton. The three position synthesis created a four bar linkage. After numerous iterations of the design the links were curved to allow the chair to reach the desired depth set forth from the ADA standards. When the linkage system was created it was decided that an electric linear actuator would be used to raise and lower the links to allow the chair to move through the desired positions. Conducting the position analysis for the system revealed the ideal location of the actuator and the transmission angles. The angles range from 73-110 degrees. From the position analysis of the linkage system the force analysis was conducted at 20 locations. Based on the iteration of this design and benchmarking of similar devices the team set out to keep the force required from the actuator low. The first 19 positions keep the forces required from the actuator below 1000 lbs. of force but at position 20 would show a significant increase. Following the force analysis the stress analysis was done. The physical model that was created revealed that the forces and stresses in the base link may be significantly large in the full size model. The bars underneath the base will take a significant amount of force. A redesign of the base may be required to add support to increase the safety of the device.

Future work/recommendations

Recommendation	Description
Redesign of the chair to increase aesthetics.	The chair could use a foot rest, handles, or an armrest to increase the comfort of the user. The chair could also include cushions. The chair could also be made to fold to make the device more compact.
Check the parts and analysis	To ensure the device will not fail, further analysis of the device should be conducted. Further analysis including the materials chosen for this design to ensure the parts will not fail.
Base Support	A redesign of the base may be necessary to reduce the forces and stresses by adding supports, changing the cross section of the parts or selecting other materials.
Try different cross sections for the link.	The cross sections of the curved links are rectangular. The links could be redesign with shapes of their cross section to compare against the square bar cross sectional shape.
The counter weight could be redesigned	The current design uses rectangular plastic tanks. The shape of the cross section could be redesigned to change the floor space the device occupies. Different types of counterweight could be tried as well such as sand water, or free weights.
The actuator for the device could be changed	The design of the actuator in this design is based off of a specific type of actuator sold on the market. As a warning: Using a different type may change the kinematics and position analysis of the design as well as how the actuator holder fits the current actuator.
Try lifting the chair with another type of motor.	Benchmarking revealed that each company uses certain of linear actuator to lift the chair. Some work could be done on using different types of motors.
Add waterproofed electrical components.	A remote for operating the lift could be devised as well as other parts.

Resources

"Aqua Creek: Lifts." Aqua Creek: Lifts. Aqua Creek Products, n.d. Web. 09 Dec. 2012. <<http://www.aquacreek.com/lifts.html>>.

Hibbeler, R.C. Statics and Mechanics of Materials, second edition. 1993, Prentice Hall

Norton, Robert. Design Of Machinery: An Introduction to the Synthesis and Analysis of Mechanisms and Machines, Fifth edition. 2012, McGraw-Hill Companies. Pearson Education.

Norton, Robert. Machine Design: An Integrated Approach, Fourth Edition. 2011, McGraw-Hill Companies.

"Spectrum Aquatics - Missoula, MT." Traveler II XRC500 ADA Pool Lift. Spectrum Aquatics, n.d. Web. 09 Dec. 2012. <<http://www.spectrumproducts.com/index.php/product/Traveler-II-XRC500-ADA-Pool-Lift/ID/2b33c2c9/fuseaction/products.detail.htm>>.

Appendix A

The Design Chart

The Design Chart below illustrates the 5 preliminary designs that were evaluated toward the beginning of the project. Each design was more of a concept when they were evaluated. The weighing factors for the chart were chosen by team based on what would seem most important at the time. Safety is the most important factor but from an economic stand point cost gets the edge with the highest weighing factor. The project is centered on cost and safety. Reliability had the lowest weighing factor as a result of the other weighing factors having a greater importance at the time. The teams' ability to analyze each design decided the weighing factor for analysis. Transfer and kinematics tied for the second least weighing factor due to the fact that once the user has been loaded into the chair the steps for transferring the user into the water and the type of motion involved did not seem as critical as the safety and cost. Power was based on the need for assistance by the user. Once the project moved forward it was understood that the user would need to be able to operate the device without outside assistance in order to be ADA compliant. The rack chain/ elevator and the arm swing were eliminated early in the project. Though the chart would indicate that the rack chain was the best concept the team was unable to excel on that design and chose to focus on the straight line linkage. Once, the team was convinced that the straight line linkage that had been designed would not work as planned the team tried to create the device using a scissor lift. The lift is in the preliminary design section of this report but was not designed early on when the design chart was created. Once the force calculations for the scissors lift were done the team went for the four bar concept.

	Designs	Safety	Cost	Reliability	Analysis	Transfer	Power	Kinematic	Rank
	Weight Factor	0.2	0.25	0.05	0.15	0.1	0.15	0.1	1
Design 1	Four Bar	4	4	5	5	4	3	2	3.85
Design 2	Six bar	4	4	5	4	4	3	3	3.8
Design 3	Rack Chain/Elevator	5	3	4	5	4	5	5	4.35
Design 4	Arm Swing	2	5	5	4	4	3	5	3.85
Design 5	Pulley Cable	3	3	5	4	4	4	5	3.7

Safety - The mechanism must never tip over at any position and keep the patient steady at all times. The process by which the patient is transferred into the water must be safe and must not expose the patient to harsh sudden movements.

- 5 – Very safe transfer and movements, and no tipping
- 4 – Safe transfer and less desirable movements, and tipping
- 3 – Less safe transfer and even less desirable movements, and tipping
- 2 – Acceptable level of safety and movements, and tipping
- 1 – Unacceptable level of safety, and movements, and tipping

Easy Assembly - The mechanism must be able to be assembled in 15 minutes.

- 5 - The mechanism can be assembled in 5 minutes.
- 4 - The mechanism can be assembled in 10 minutes.
- 3 - The mechanism can be assembled in 15 minutes.
- 2 - The mechanism can be assembled in 20 minutes.
- 1 - The mechanism can be assembled in more than 20 minutes.

Complexity - The mechanism is designed to be assembled with the least parts and as simple as possible.

- 5 – The mechanism has 2 parts.
- 4 - The mechanism has 3 parts.
- 3 - The mechanism has 4 parts.
- 2 - The mechanism has 5 parts.
- 1 - The mechanism has 6 or more parts.

Cost - The cost of the mechanism including manufacturing cost and product price.

- 5 - The cost of the mechanism is under \$600.
- 4 - The cost of the mechanism is under \$900.
- 3 - The cost of the mechanism is under \$1200.
- 2 - The cost of the mechanism is under \$1500.
- 1 - The cost of the mechanism is over \$1500.

Reliability - The mechanism must be easy to repair and maintain.

5 - The reparation and maintenance of the mechanism are simple which can be done by the customer with manual.

4 - The reparation and maintenance of the mechanism will take some time by the customer with manual or simple if call specialist.

3 - The reparation and maintenance of the mechanism is not complex but must be done by specialist.

2 - The reparation and maintenance of the mechanism is complex and must be done by specialist.

1 - The reparation and maintenance of the mechanism is very complex and must be done by specialist.

Analysis - The mechanism must be easy to analysis with basic equations, and also capable with computer software.

5 - The analysis of the mechanism uses basic equations and does not require computer software.

4 - The analysis of the mechanism uses advance equations and does not require computer software.

3 - The analysis of the mechanism uses basic equations and requires computer software. The mechanism is capable to computer software.

2 - The analysis of the mechanism uses advance equations and requires computer software. The mechanism is capable to computer software.

1 - The analysis of the mechanism uses advance equations and not capable to computer software.

User friendly – The mechanism is easy to understand.

- 5 - The mechanism is easy to use that doesn't need a manual.
- 4 - The mechanism is easy to use after the user read the manual.
- 3 - The mechanism takes time to get familiar with after the user follow the manual several times.
- 2 - The mechanism is complicated and may cause confusions.
- 1 - The mechanism is hard to understand.

Manually Self-operational – The mechanism must be able to self-operate by the patient without assistant and any kind of electronic parts. The mechanism can have extra mechanical parts to achieve manual self-operation.

- 5 – The mechanism can self-operate and use minimum 1 manual power method.
- 4 – The mechanism can self-operate and use minimum 2 manual power methods.
- 3 - The mechanism can self-operate and use minimum 3 manual power methods.
- 2 – The mechanism can self-operate and use minimum 4 or manual power methods.
- 1 – The mechanism can't self-operate without any kind of electronic parts.

Transfer - The transfer steps for the mechanism should be as less as possible. This is the number of steps to the water once the patient is loaded into the chair.

- 5 – One step process
- 4 – Two step process
- 3 – Four or Three step process
- 2 – Five or six step process
- 1 – Seven or more step process

Kinematic - The motion of the mechanism must be simple, straight movements are preferred.

- 5 - The motion only contains horizontal and vertical movements.

- 4 - The motion contains mainly horizontal and vertical and some curve movements.
- 3 - The motion contains mainly curve movements and some horizontal and vertical movements.
- 2 - The motion contains only curve movements.
- 1 - The motion contains horizontal, vertical, curve and other movements.

Power -.The mechanism is ideally man powered (non electric) and self operational. This is a measure of the ability.

- 5 - The mechanism requires only the patient and no outside assistance for operation.
- 4 - The mechanism requires the patient and outside (non electric) assistance for operation.
- 3 - The mechanism requires an assistant and no electric motors for operation.
- 2 - The mechanism requires an assistant and an electric motor for operation.
- 1 - The mechanism requires solely electric motor(s) for operation.

Position analysis

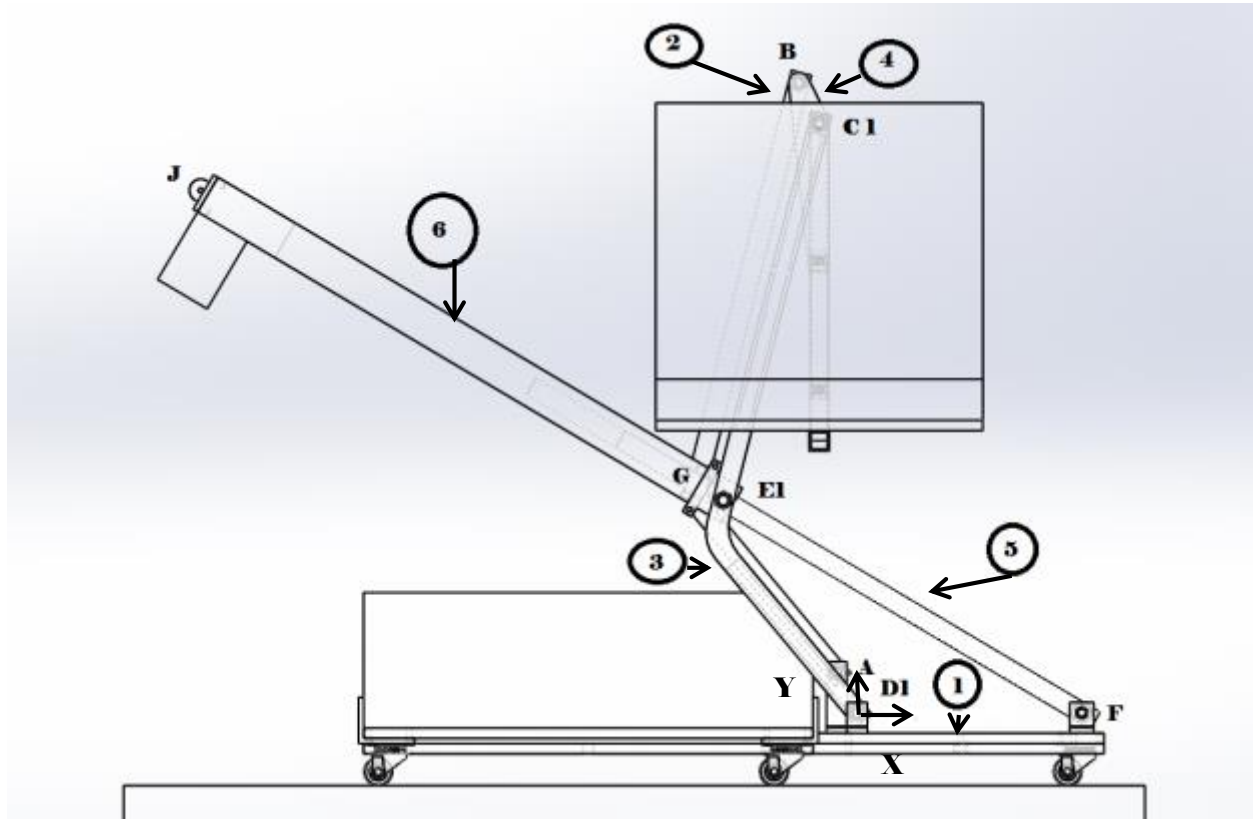


Figure 72: (X-Y) plane view (Side view) of the design with the actuator fully extended.

Each of the following images show the 20 positions used in the position analysis. Link 6 is omitted from each drawing but will maintain its length and will be collinear with link 5 through each step. Table 4 on page 98 shows each change and stroke length affects the transmission angle.

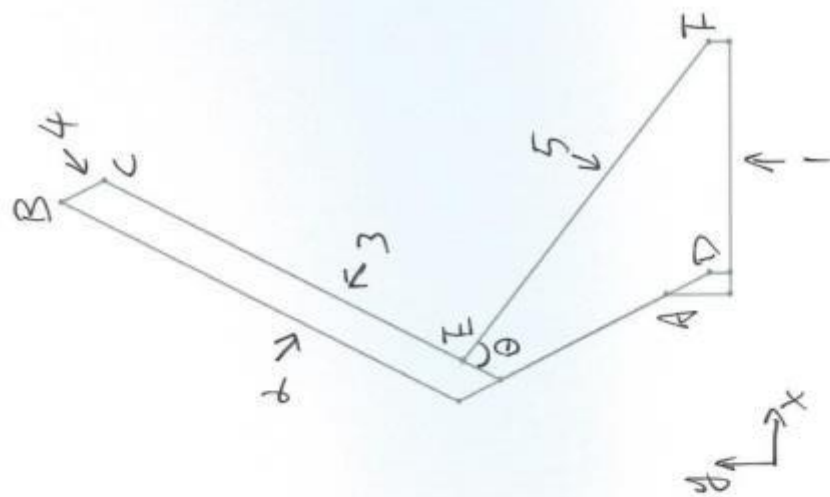
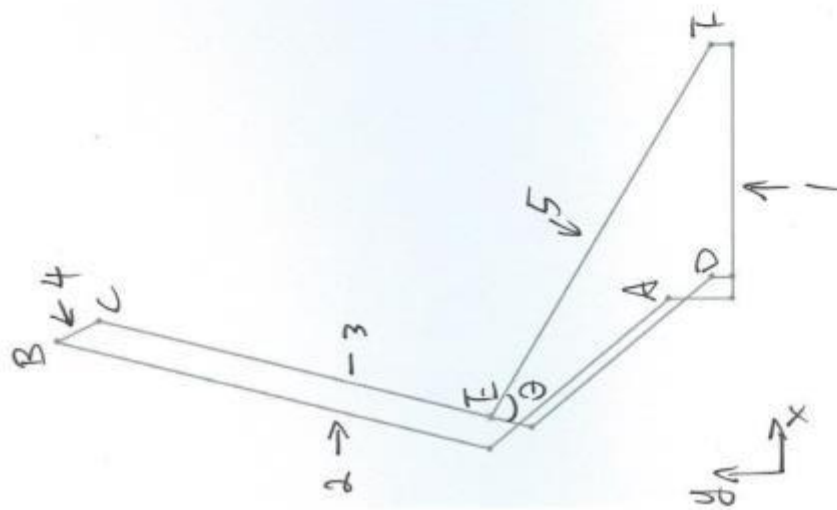


Figure 73: positions 1-2 show the linear actuator (link 5) moving from a stroke length of 20.39 in. as seen on the left to 19 in. as seen on the right.

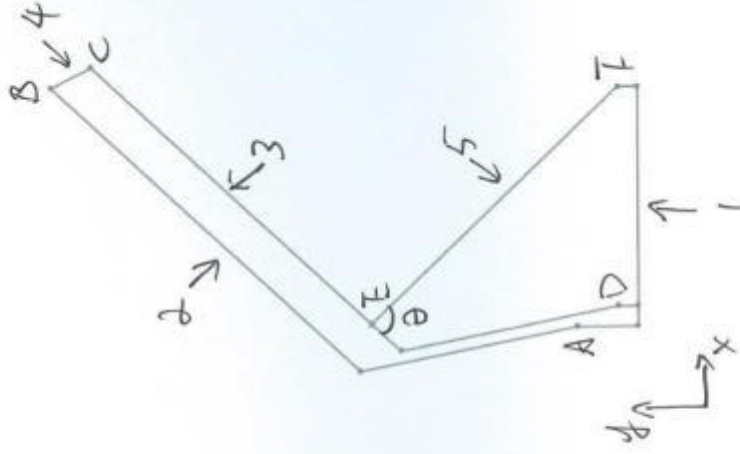
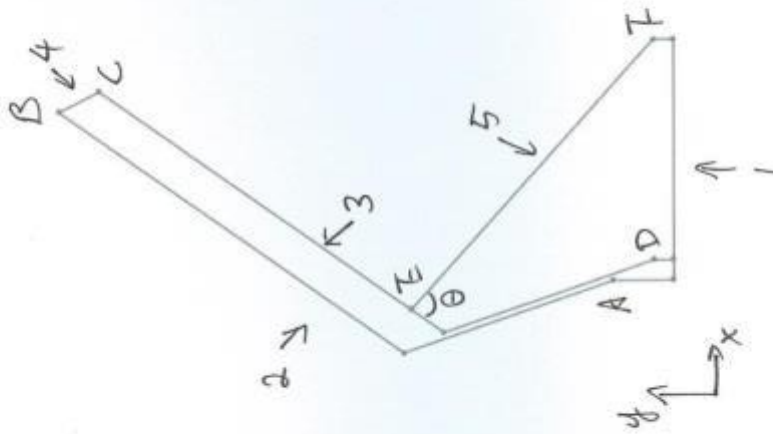


Figure 74: positions 3-4 show the linear actuator (link 5) moving from a stroke length of 18 in. as seen on the left to 17 in. as seen on the right.

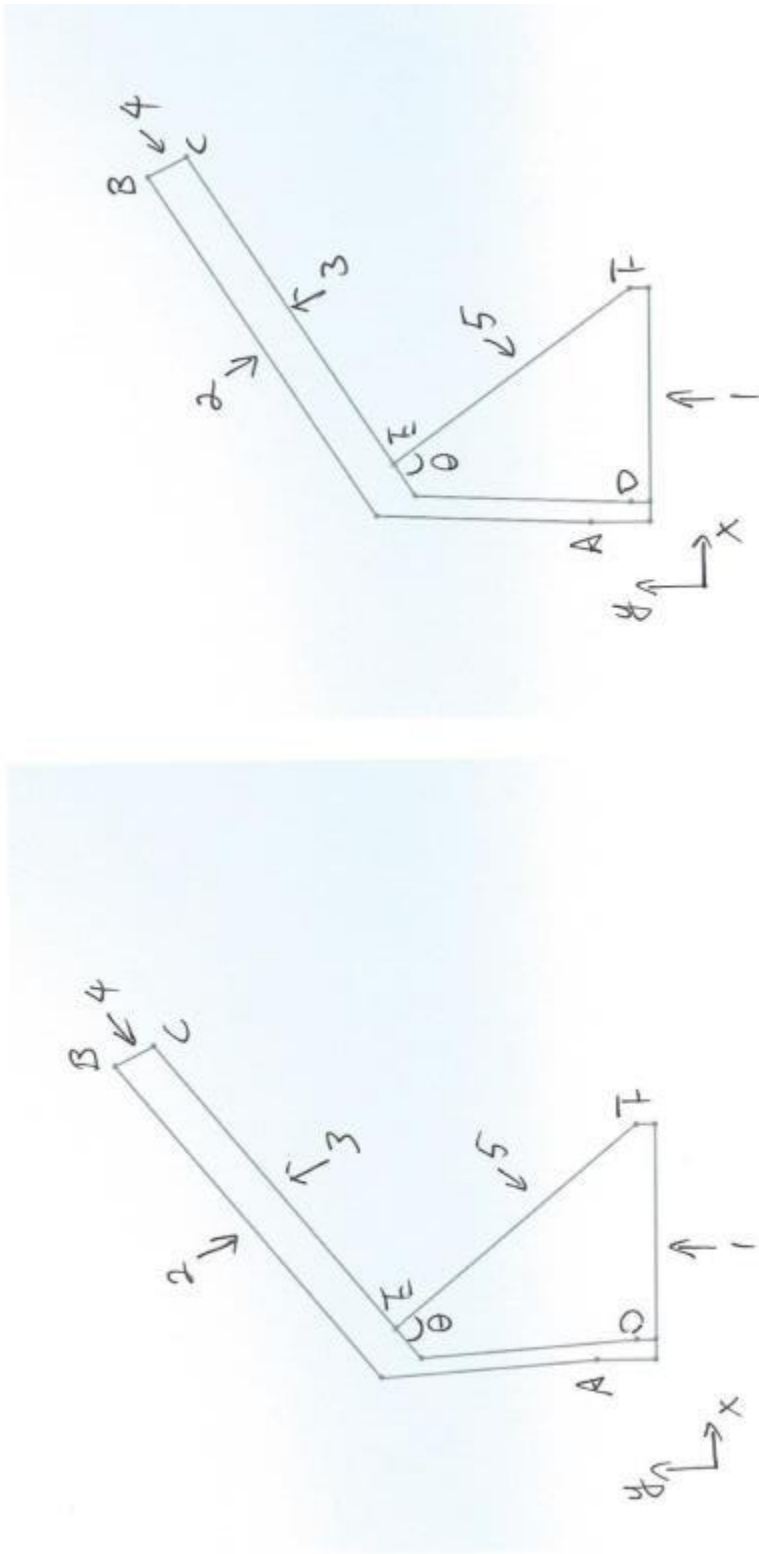


Figure 75: positions 5-6 show the linear actuator (link 5) moving from a stroke length of 16 in. as seen on the left to 15 in. as seen on the right.

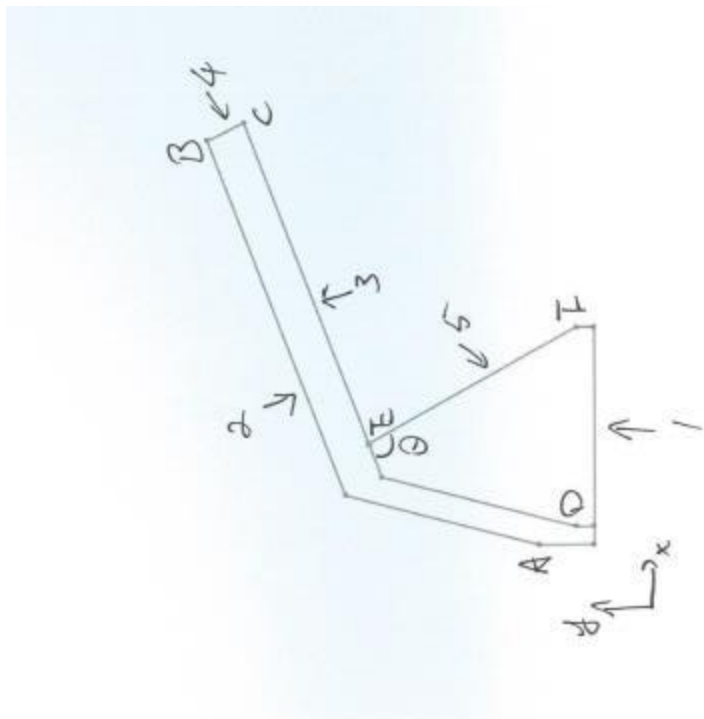
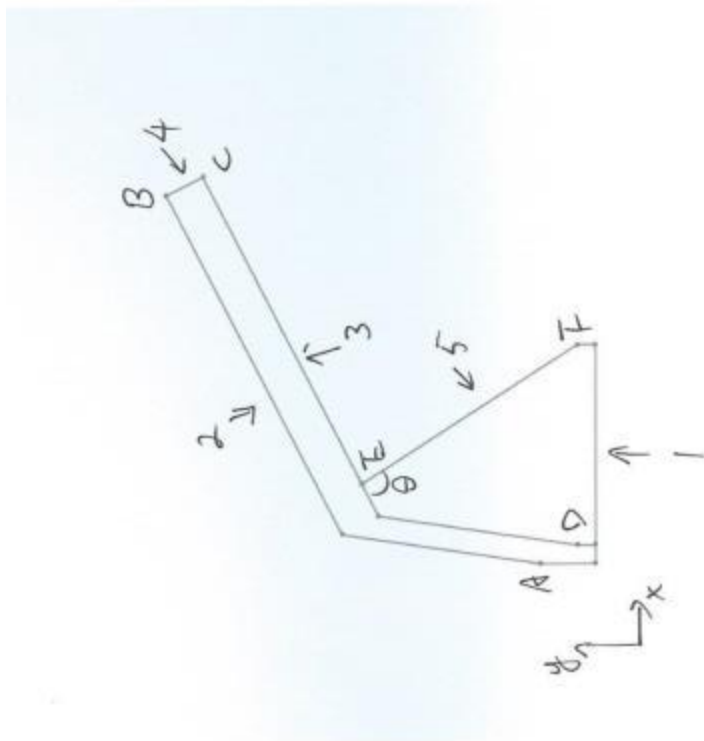


Figure 76: positions 7-8 show the linear actuator (link 5) moving from a stroke length of 14 in. as seen on the left to 13 in. as seen on the right

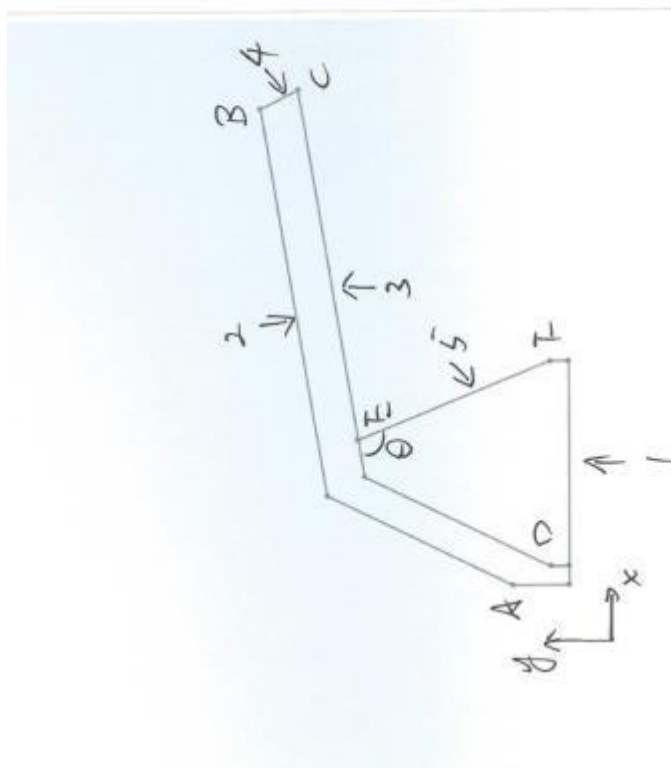
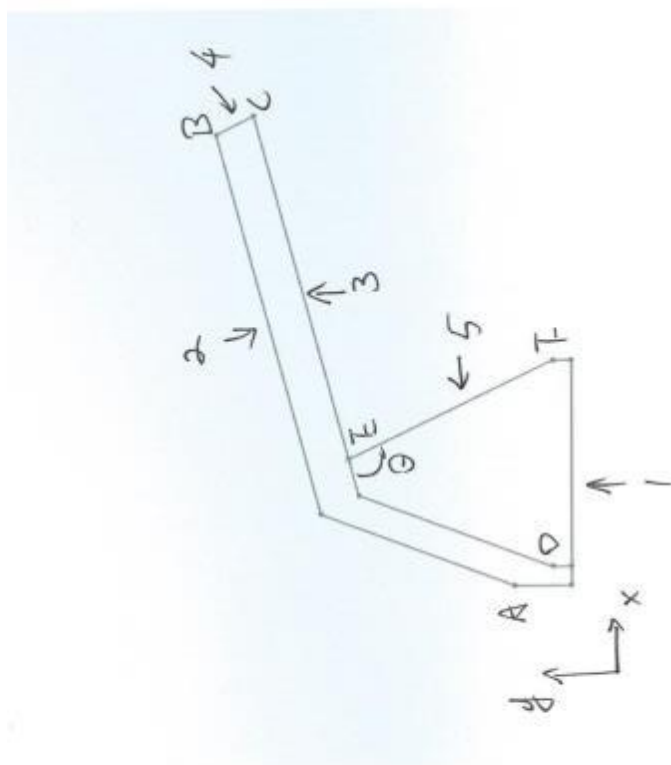


Figure 77: positions 9-10 show the linear actuator (link 5) moving from a stroke length of 12 in. as seen on the left to 11 in. as seen on the right.

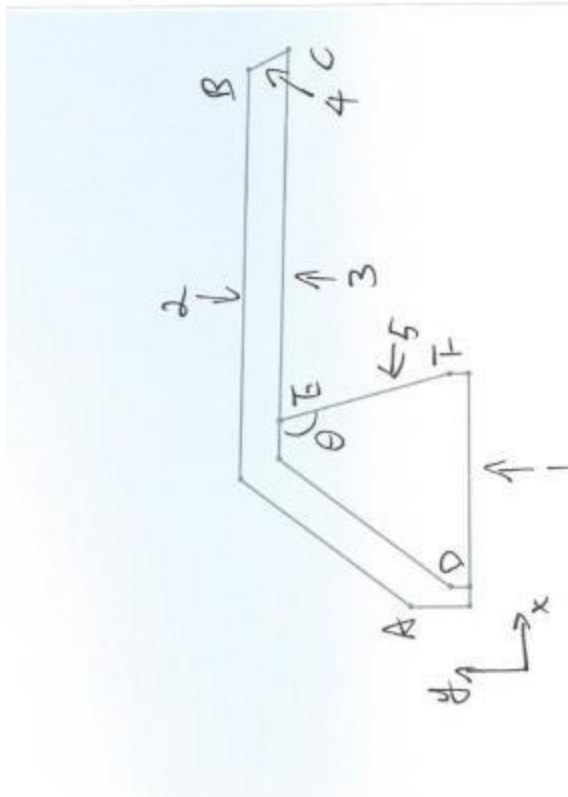
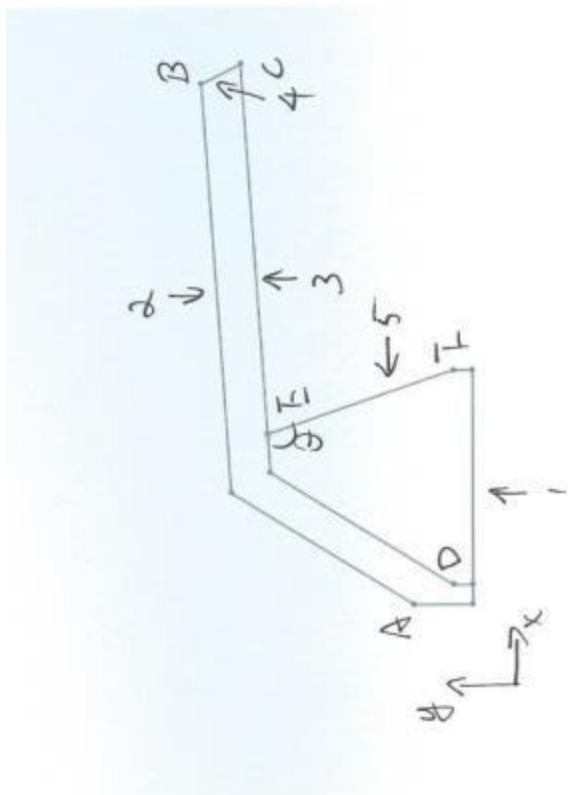


Figure 78: positions 11-12 show the linear actuator (link 5) moving from a stroke length of 10 in. as seen on the left to 9 in. as seen on the right.

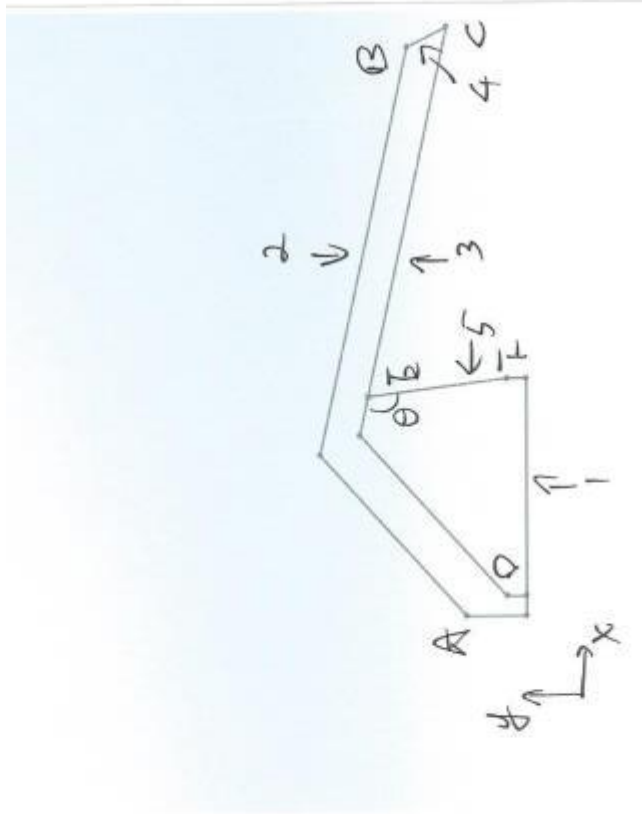
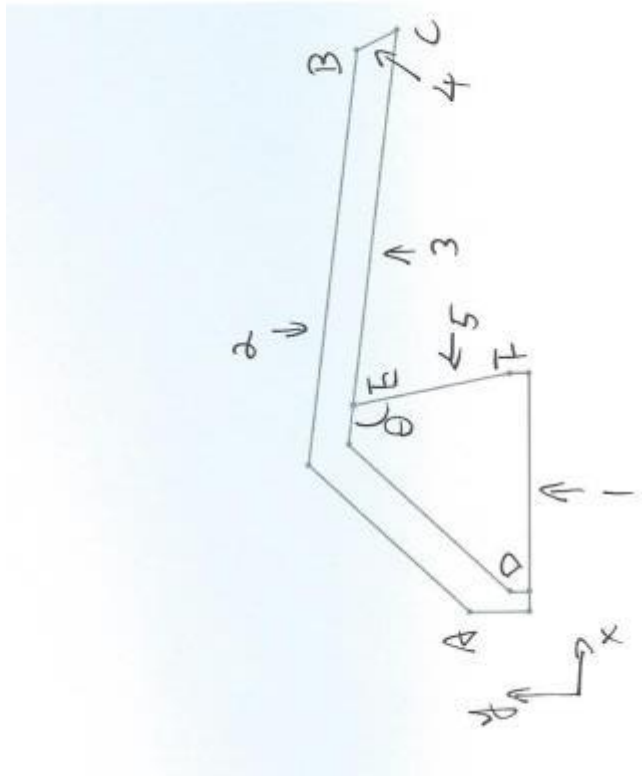


Figure 79: positions 13-14 show the linear actuator (link 5) moving from a stroke length of 8 in. as seen on the left to 7 in. as seen on the right

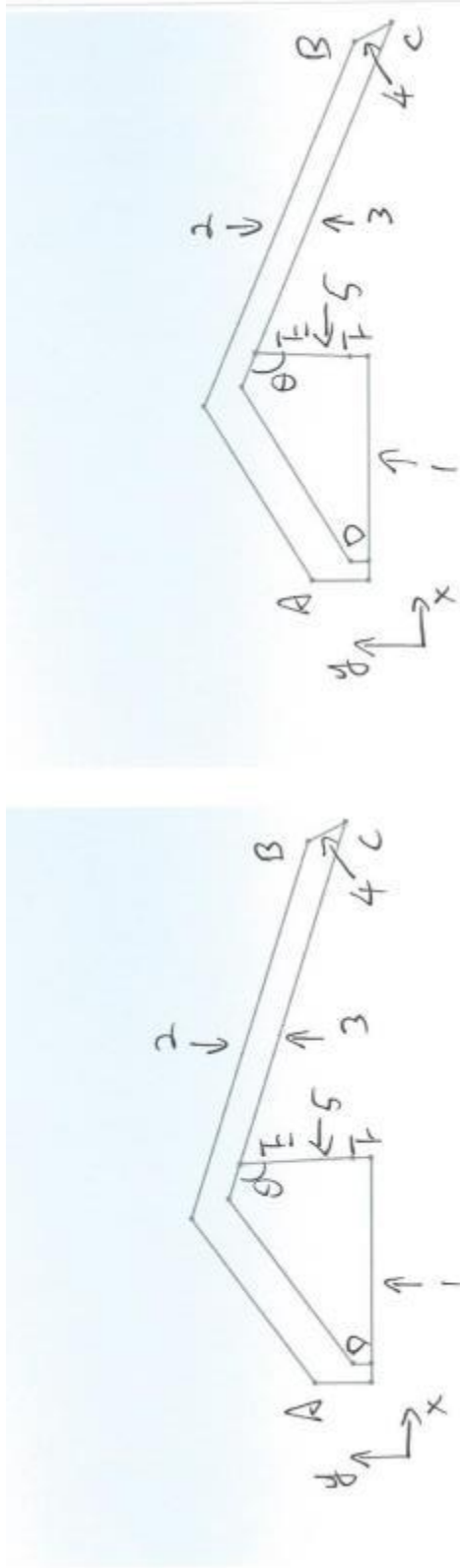


Figure 80: positions 15-16 show the linear actuator (link 5) moving from a stroke length of 6 in. as seen on the left to 5 in. as seen on the right.

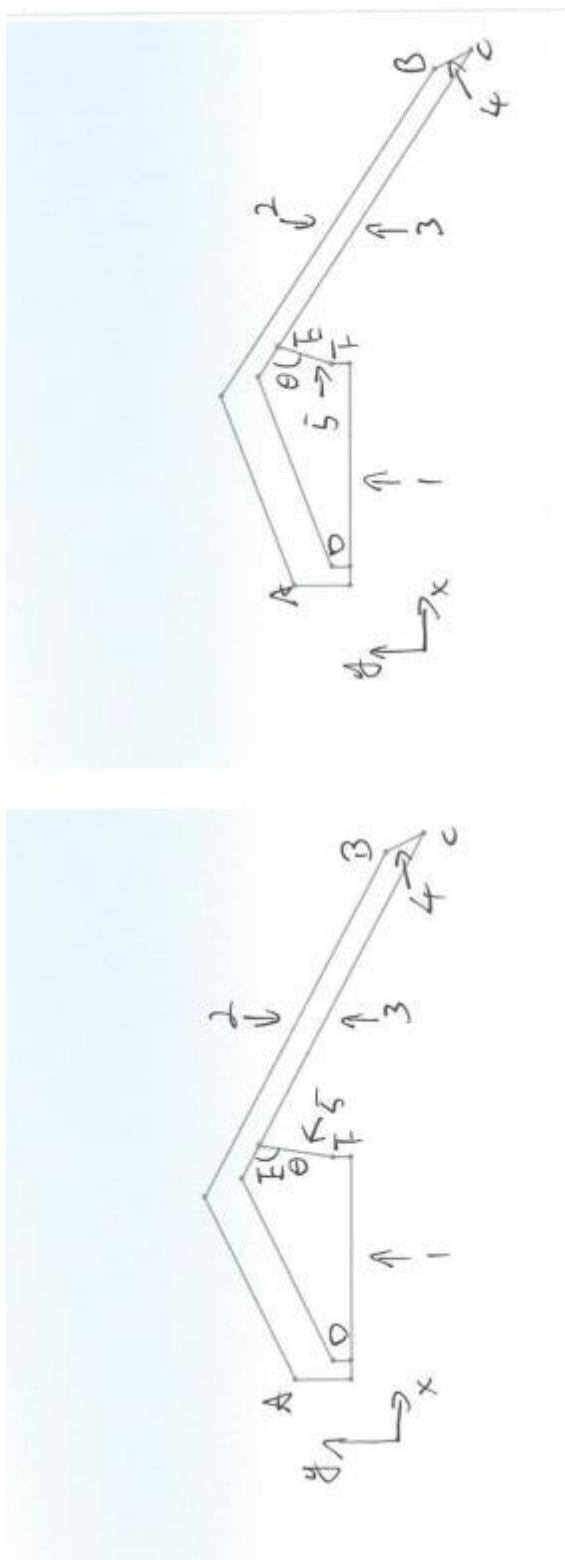


Figure 81: positions 17-18 show the linear actuator (link 5) moving from a stroke length of 4 in. as seen on the left to 3 in. as seen on the right.

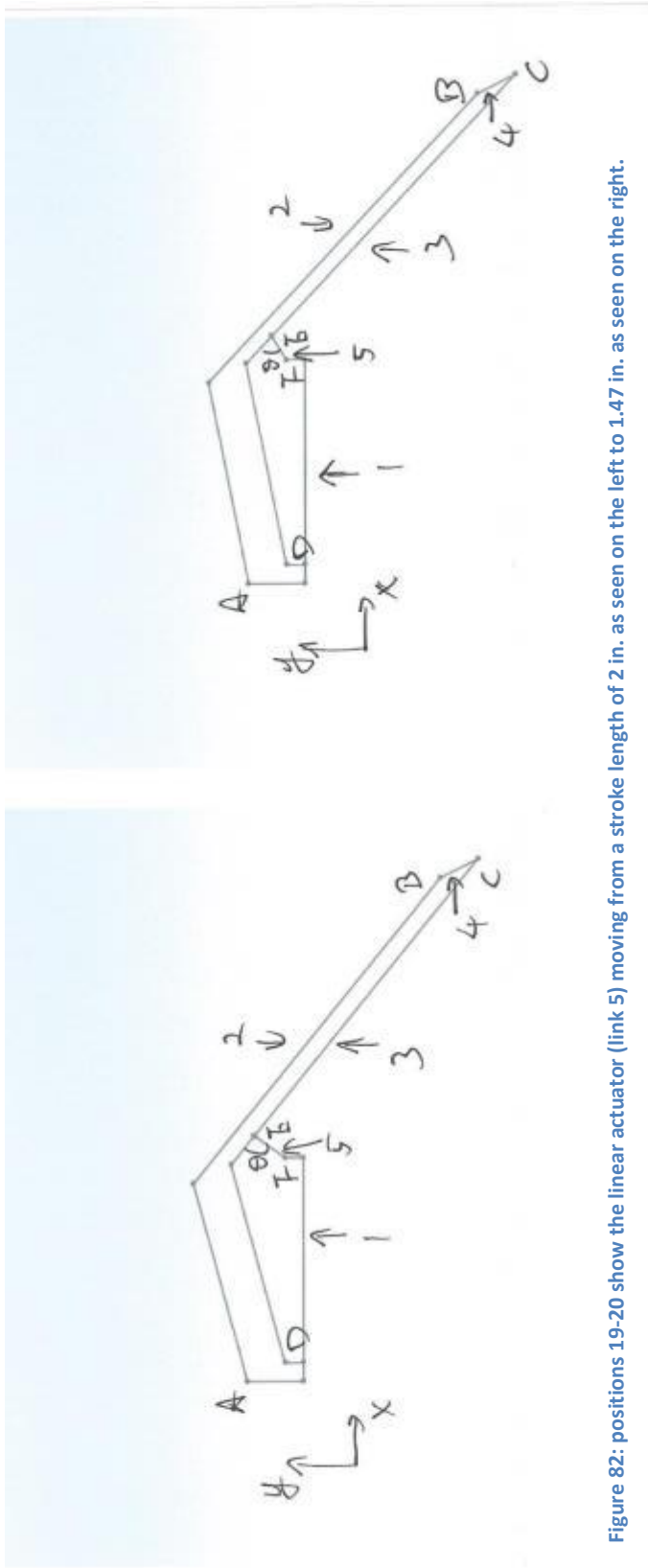


Figure 82: positions 19-20 show the linear actuator (link 5) moving from a stroke length of 2 in. as seen on the left to 1.47 in. as seen on the right.

Table 4: Stroke Length vs. Transmission Angle

Stroke Length(in.)	Transmission Angle
20.39	73.71
19	79.68
18	83.39
17	86.78
16	89.89
15	92.8
14	95.51
13	98.05
12	100.42
11	102.63
10	104.65
9	106.48
8	108.04
7	109.28
6	110.04
5	110.06
4	108.78
3	104.8
2	93.11
1.47	74.35

Appendix C

Force analysis Excel Data

Table 3: Counter Weight (x-y) plane force results

Fw(lbs.)	a(in.)	b(in.)	Fcounter(lbs.)
300	18.54	23.47	236.983

Table 4: Counter Weight (y-z) force results

Fw(lbs.)	a(in.)	b(in.)	Fcounter(lbs.)
300	4.19	7.62	164.960

Table 5: Chair Bar (x-y) force results

Fw(lbs.)	F2y(lbs.)
300	300

Table 6: Chair Bar (y-z) force results

Fw(lbs.)	a(in.)	b(in.)	F2y(lbs.)	F2z(lbs.)	F1z(lbs.)
300	8.75	13	300	201.9231	201.923

Table 7: Chair Back Angle Bar (y-z) force results

F1z(lbs.)	a(in.)	Mi(lbs.-in.)
201.9231	6.3	1272.115

Table 8: Chair Back Straight Bar (y-z) results

F2z(lbs.)	F1z(lbs.)	F3z(lbs.)
201.923	201.923	0

Table 9: Main Link (x-y) (Kinematic link 3) force results

Stroke Length (inch)	F2x (lbs)	F2y (lbs)	θ (Degree)	θ (Radian)	α (Degree)	α (Radian)	a (inch)	b (inch)	c (inch)	d (inch)	Factuator (Joint E) (lbs)	Fax	Fay	F4x (lbs)	F4y (lbs)	F4 (Joint D) (lbs)
20.39	0	0	300	73.71	1.286	14.35	0.2505	28.8	10.39	1.84	6.54	84.7134	50.179	84.713	350.179	360.280
19	0	0	300	79.68	1.391	27.27	0.4760	28.48	11.59	-4.65	4.06	-164.8058	-126.872	-164.806	173.128	239.028
18	0	0	300	83.39	1.455	35.41	0.6180	27.53	12.05	-8.63	2.37	-261.1315	-235.289	-261.132	64.711	269.030
17	0	0	300	86.78	1.515	42.9	0.7487	26.17	12.25	-12.15	0.78	-318.6497	-331.357	-318.650	-31.357	320.189
16	0	0	300	89.89	1.569	49.9	0.8709	24.5	12.26	-15.25	-0.72	-348.7477	-415.769	-348.748	-115.769	367.461
15	0	0	300	92.8	1.620	56.53	0.9866	22.57	12.09	-17.97	-2.13	-359.5719	-490.035	-359.572	-190.035	406.701
14	0	0	300	95.51	1.667	62.84	1.0968	20.46	11.79	-20.35	-3.44	-355.8827	-554.983	-355.883	-254.983	437.800
13	0	0	300	98.05	1.711	68.92	1.2029	18.19	11.36	-22.4	-4.67	-340.4254	-610.871	-340.425	-310.871	461.010
12	0	0	300	100.42	1.753	74.78	1.3052	15.81	10.82	-24.14	-5.81	-315.9037	-658.162	-315.904	-358.162	477.572
11	0	0	300	102.63	1.791	80.48	1.4046	13.33	10.19	-25.59	-6.85	-284.1505	-698.030	-284.150	-398.030	489.050
10	0	0	300	104.65	1.826	86.04	1.5017	10.79	9.48	-26.76	-7.81	-245.7033	-729.671	-245.703	-429.671	494.962
9	0	0	300	106.48	1.858	91.48	1.5966	8.2	8.69	-27.67	-8.67	-202.2322	-754.741	-202.232	-454.741	497.682
8	0	0	300	108.04	1.886	96.83	1.6900	5.59	7.85	-28.31	-9.44	-153.0771	-772.388	-153.077	-472.388	496.571
7	0	0	300	109.28	1.907	102.11	1.7822	2.96	6.95	-28.7	-10.13	-98.4267	-782.422	-98.427	-482.422	492.360
6	0	0	300	110.04	1.921	107.34	1.8734	0.33	5.99	-28.85	-10.72	-37.0970	-786.641	-37.097	-486.641	488.053
5	0	0	300	110.06	1.921	112.55	1.9644	-2.29	5	-28.76	-11.22	34.1009	-784.180	34.101	-484.180	485.380
4	0	0	300	108.78	1.899	117.79	2.0558	-4.91	3.95	-28.44	-11.63	122.9464	-775.377	122.946	-475.377	491.019
3	0	0	300	104.8	1.829	123.15	2.1494	-7.54	2.85	-27.85	-11.94	252.0528	-759.912	252.053	-459.912	524.452
2	0	0	300	93.11	1.625	128.97	2.2510	-10.33	1.62	-26.94	-12.17	531.1190	-734.792	531.119	-434.792	686.390
1.47	0	0	300	74.35	1.298	132.98	2.3209	-12.19	0.77	-26.15	-12.26	1170.0699	-713.373	1170.070	-413.373	1240.944

Table 10: Base Link (x-y) force results

Factuator (Joint E) (lbs)	F4x (lbs)	F4y (lbs)	ϕ (degree)	ϕ (radian)	a	d	b	c	e	F5y	F6x	F7y
98.460	84.713	350.179	30.63	0.535	5.5	5.5	5.09	5.91	1.5	362.102	169.436	62.0869
-207.984	-164.806	173.128	37.59	0.656	5.5	5.5	5.09	5.91	1.5	116.999	-329.612	-183.001
-351.498	-261.132	64.711	42.01	0.733	5.5	5.5	5.09	5.91	1.5	-17.692	-522.304	-317.647
-459.712	-318.650	-31.357	46.12	0.805	5.5	5.5	5.09	5.91	1.5	-129.444	-637.299	-429.444
-542.668	-348.748	-115.769	50.01	0.873	5.5	5.5	5.09	5.91	1.5	-222.063	-697.495	-522.063
-607.805	-359.572	-190.035	53.73	0.938	5.5	5.5	5.09	5.91	1.5	-299.282	-719.144	-599.282
-659.287	-355.883	-254.983	57.34	1.001	5.5	5.5	5.09	5.91	1.5	-363.213	-711.669	-663.275
-699.323	-340.425	-310.871	60.87	1.062	5.5	5.5	5.09	5.91	1.5	-414.896	-680.851	-714.896
-730.050	-315.904	-358.162	64.36	1.123	5.5	5.5	5.09	5.91	1.5	-455.500	-631.807	-755.5
-753.650	-284.150	-398.030	67.85	1.184	5.5	5.5	5.09	5.91	1.5	-486.708	-568.301	-786.708
-769.929	-245.703	-429.671	71.39	1.246	5.5	5.5	5.09	5.91	1.5	-507.863	-491.407	-807.863
-781.365	-202.232	-454.741	75.01	1.309	5.5	5.5	5.09	5.91	1.5	-521.060	-404.333	-821.095
-787.411	-153.077	-472.388	78.79	1.375	5.5	5.5	5.09	5.91	1.5	-525.318	-306.154	-825.318
-788.589	-98.427	-482.422	82.83	1.446	5.5	5.5	5.09	5.91	1.5	-520.447	-196.853	-820.447
-787.515	-37.097	-486.641	87.3	1.524	5.5	5.5	5.09	5.91	1.5	-507.940	-74.194	-807.94
-784.922	34.101	-484.180	92.49	1.614	5.5	5.5	5.09	5.91	1.5	-486.062	68.202	-786.062
-785.064	122.946	-475.377	99.01	1.728	5.5	5.5	5.09	5.91	1.5	-453.028	245.893	-753.028
-800.623	252.053	-459.912	108.35	1.891	5.5	5.5	5.09	5.91	1.5	-402.352	504.106	-702.352
-906.645	531.119	-434.792	125.86	2.197	5.5	5.5	5.09	5.91	1.5	-301.123	1062.238	-601.123
-1370.389	1170.070	-413.373	148.64	2.594	5.5	5.5	5.09	5.91	1.5	-105.420	2340.264	-405.216

Table 11: Base Link Wheel (x-y) force results

F7y(lbs.)	Fwheel(lbs.)
62.0869	62.0869
-	
183.001	-183.001
-	
317.647	-317.647
-	
429.444	-429.444
-	
522.063	-522.063
-	
599.282	-599.282
-	
663.275	-663.275
-	
714.896	-714.896
-755.5	-755.5
-	
786.708	-786.708
-	
807.863	-807.863
-	
821.095	-821.095
-	
825.318	-825.318
-	
820.447	-820.447
-807.94	-807.94
-	
786.062	-786.062
-	
753.028	-753.028
-	
702.352	-702.352
-	
601.123	-601.123
-	
405.216	-405.216

Table 12: Base Bar (x-y) force results

F5y(lbs.)	F6x(lbs.)	F7y(lbs.)	a(in.)	b(in.)	c(in.)	F9y(lbs.)	F8x(lbs.)
362.1017	169.4355	62.0869	5.5	5.5	9.5	245.5829	169.4355
116.9994	-329.612	-	5.5	5.5	9.5	-38.2112	-329.612
-17.6924	-522.304	-	5.5	5.5	9.5	-194.144	-522.304
-129.444	-637.299	-	5.5	5.5	9.5	-323.566	-637.299
-222.063	-697.495	-	5.5	5.5	9.5	-430.81	-697.495
-299.282	-719.144	-	5.5	5.5	9.5	-520.222	-719.144
-363.213	-711.669	-	5.5	5.5	9.5	-594.283	-711.669
-414.896	-680.851	-	5.5	5.5	9.5	-654.09	-680.851
-455.5	-631.807	-	5.5	5.5	9.5	-701.105	-631.807
-486.708	-568.301	-	5.5	5.5	9.5	-737.24	-568.301
-507.863	-491.407	-	5.5	5.5	9.5	-761.736	-491.407
-521.06	-404.333	-	5.5	5.5	9.5	-777.037	-404.333
-525.318	-306.154	-	5.5	5.5	9.5	-781.948	-306.154
-520.447	-196.853	-	5.5	5.5	9.5	-776.308	-196.853
-507.94	-74.1941	-	5.5	5.5	9.5	-761.825	-74.1941
-486.062	68.20187	-	5.5	5.5	9.5	-736.493	68.20187
-453.028	245.8929	-	5.5	5.5	9.5	-698.243	245.8929
-402.352	504.1056	-	5.5	5.5	9.5	-639.566	504.1056
-301.123	1062.238	-	5.5	5.5	9.5	-522.353	1062.238
-105.42	2340.264	-	5.5	5.5	9.5	-295.632	2340.264

Table 13: Tank Bar (x-y) force results

F9y(lbs.)	F8x(lbs.)	Fcounter(lbs.)	F10y(lbs.)	F10x(lbs.)
245.583	169.436	236.983	482.566	169.436
-38.211	-329.612		198.772	-329.612
-194.144	-522.304		42.84	-522.304
-323.566	-637.299		-86.583	-637.299
-430.81	-697.495		-193.827	-697.495
-520.222	-719.144		-283.238	-719.144
-594.283	-711.669		-357.299	-711.669
-654.09	-680.851		-417.107	-680.851
-701.105	-631.807		-464.121	-631.807
-737.24	-568.301		-500.257	-568.301
-761.736	-491.407		-524.753	-491.407
-777.037	-404.333		-540.054	-404.333
-781.948	-306.154		-544.964	-306.154
-776.308	-196.853		-539.324	-196.853
-761.825	-74.194		-524.842	-74.1941
-736.493	68.202		-499.509	68.2027
-698.243	245.893		-461.26	245.893
-639.566	504.106		-402.582	504.105
-522.353	1062.238		-285.369	1062.238
-295.632	2340.264		-58.6482	2340.264

Appendix D

Stress Analysis Excel Data

Table 14: Chair Bar Stresses

Chair Bar Body										
Fw(lbs.)	F2y(lbs.)	F2z(lbs.)	a(in.)	Ma(lbs.-in.)	b(in.)	h(in.)	l(in.)	σ_y (psi)	σ_z (psi)	σ' (psi)
300	300	201.9231	8.1	2430	1	1	0.083	300	14580	14432.34
Point C at bar										
Rrod(in.)	Arod(in.^2)	τ_C at bar (psi)								
0.25	0.196	763.9437								
Point C at Rod										
Rrod(in.)	Arod(in.^2)	τ_C at rod (psi)	σ_z (psi)	σ' (psi)						
0.25	0.196	1527.887	807.6923	2707.306						
Point H at bar										
Rpin(in.)	Apin(in.^2)	τ_H at bar (psi)								
0.125	0.049	3055.775								
Point H at Pin										
Rpin(in.)	Apin(in.^2)	τ_H at pin (psi)	σ_z (psi)							
0.125	0.049	6111.55	1615.385	10646.96						

Table 15: Chair Back Angle Bar Stresses

F1z(lbs.)	Mi(lbs.-in.)	b(in.)	h(in.)	l(in.)	σ_z (psi)	σ' (psi)	
201.923	1272.115	1	1	0.0833	7632.692	5397.128	
Dpin(in.)	b(in.)	h(in.)	lpin	lbar	lsum	σ_z (psi)	σ' (psi)
0.25	0.2	0.7	0.0001	0.006	0.006	26913.21	19030.52

Table 16: Chair Back Straight Bar Stresses

Mi(lbs.-in.)	b(in.)	h(in.)	l(in.)	σ_z (psi)	σ' (psi)
1272.115	1	1	0.0833	7632.692	5397.128

Table 17: Main Link Stresses (Kinematic link 3)

F4x (lbs)	F4y (lbs)	a(in.)	c(in.)	b(in.)	h(in.)	l(in.)	σ_x (psi)	σ_y (psi)	σ' (psi)
84.7134	350.1792	8.45	7.04	0.5	1	0.041667	8589.937	29583.14	26359.66

Table 18: Actuator Holder Stresses

Factuator (Joint E) (lbs)	b(in.)	h(in.)	Aplate(in.^2)	$\sigma_{tensile}$ (psi)
906.6454197	4.1	1.96	8.036	-112.823
Point E at bar				
Rpin(in.)	Apin(in.^2)	τ_C (psi)		
0.25	0.19635	2308.75		
Point E at Rod				
Rpin(in.)	Apin(in.^2)	τ_C (psi)		
0.25	0.19635	4617.51		

Table 19: Base Link Stresses

Factuator (Joint E) (lbs)	F4 (Joint D) (lbs)								
906.6454197	686.389838								
Point D at bar									
Rpin(in.)	Apin(in.^2)	TD							
0.25	0.19634954	1747.877							
Point D at Rod									
Rpin(in.)	Apin(in.^2)	τ_D							
0.25	0.19634954	3495.755							
Point F at bar									
Rpin(in.)	Apin(in.^2)	TF							
0.25	0.19634954	-2308.75							
Point F at Rod									
Rpin(in.)	Apin(in.^2)	τ_F							
0.25	0.19634954	-4617.51							
F6x(lbs)	M6x(lbs.-in.)	b(in.)	h(in.)	l(in.)	σ_y (psi)	Dpin(in.)	Apin(in.^2)	τ_{6x} (psi)	σ' (psi)

1062.237919	-7305.5018	14	0.5	0.145833	12523.7	0.25	0.049087	21639.73	38513.06
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Table 20: Base Bar Stresses

F9y(lbs)	F6x(lbs)	M6x(lbs.-in.)	b(in.)	h(in.)	I(in.)	σ_y (psi)	σ' (psi)
-781.948	1062.238	-7428.5	16.75	0.5	0.174479	-10643.8	8865.44
Point 6x at bar							
Rpin(in.)	Apin(in.^2)	τ_{6x} (psi)					
0.25	0.19635	2704.967					
Point 6x at pin							
Rpin(in.)	Apin(in.^2)	τ_{6x} (psi)					
0.25	0.19635	5409.933					

Table 21: Tank Bar Stresses

F9y(lbs)	F10x(lbs)	a(in.)	M10x(lbs.-in.)	b(in.)	h(in.)	I(in.)	σ_y (psi)	σ' (psi)
-781.948	1062.238	0.94	-735.031	2.5	0.5	0.026042	-7056.29	6844.427
Point 10x at bar								
Rpin(in.)	Apin(in.^2)	τ_{10x}						
0.25	0.19635	2704.967						
Point 10x at pin								
Rpin(in.)	Apin(in.^2)	τ_{10x}						
0.25	0.19635	5409.933						